2018

Analysis of the Gas Production from Marcellus Shale Horizontal Wells Using Decline Curves

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ANALYSIS OF THE GAS PRODUCTION FROM MARCELLUS SHALE HORIZONTAL WELLS USING DECLINE CURVES

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Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of
Master of Science
in
Petroleum and Natural Gas Engineering

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Morgantown, West Virginia 2018

Keywords Decline curve analysis, Shale Gas, DCA, Marcellus shale

ABSTRACT

ANALYSIS OF THE GAS PRODUCTION FROM MARCELLUS SHALE HORIZONTAL WELLS USING DECLINE CURVES

Dalal Alsaadoun

Many challenges present themselves when production is being forecasted in ultra-low permeability unconventional reservoir systems. Some of the major challenges are the lack of understanding of the interaction among the fluid flow, the hydraulic fracturing, the reservoir characteristics in these complex systems, and the limited production history. Therefore, the production performance of the shale gas wells over the longer time periods has not been established. A familiar technique for predicting the future production rates, when the only available data are past production rates, is Decline Curve Analysis (DCA). Several DCA methods have been proposed for shale wells, but their application remains problematic. Therefore, a reliable and yet easy to apply predictive tool for accurate prediction of the production performance of the Shale Gas wells is Needed.

Marcellus Shale is an important source of natural gas located in the Appalachian Basin. In this study, a number of production data were collected from Marcellus shale gas wells to be analyzed and to develop a reliable and easy methodology to apply a predictive tool in order to improve the conventional DCA for obtaining an accurate prediction for the production performance. A Prediction Technique has been developed and proposed to continuously adjust the conventional DCA prediction for the limited production history of the Marcellus Shale Gas Wells.

ACKNOWLEDGEMENTS

I would like to express my most profound appreciation to my research advisor Dr. Kashy Aminian, the chair of my advisory committee for being my teacher and mentor, for providing me with guidance, and advice, and for giving me this great opportunity of acquiring more knowledge while working in this research, I also would like to thank my committee members Dr. Sam Ameri and Dr. Mehrdad Zamirian for their support, encouragement, and suggestions.

I am also very grateful for my family for believing in me, supporting and encouraging me during the pursuit of this degree. I would like to thank my parents for their love, support, and guidance in achieving my goals in life.

I would also like to thank my supportive friends, for providing me with the mental and emotional support along this journey.

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A	Area
a	Darcy flow coefficient
b	Non Darcy flow coefficient
b	Arps hyperbolic parameter theoretically between 0 and 1
B_{oi}	formation volume factor
C_A	Dietz shape Factor
c_g	gas compressibility
c_t	total compressibility
D_i	Initial decline rate of the function
D_∞	decline constant at infinite time
D_1	decline constant "intercept" at 1 time unit.
F_{tad}	the effect of pressure on gas properties
F_{NDi}	Non Darcy flow ratio
Gp	$cumilative\ gas\ production.$
h	thickness
J	productivity index
J_g	gas productivity index
k	Formation permeability
m	slope
n	time exponent
N_{pi}	cumulative oil production, STB
p_i	initial pressure, psia
p_{wf}	bottomhole flowing pressure, psia
P_{sc}	Pressure at standard condition
P_p	pseudopressure
q_i	Initial stabilized rate
$q(t)$	surface rate of flow at time *t*
qD	dimensionless flow rate
q_{Dd}	decline curve dimensionless rate
r_e	external boundary radius
r_w	wellbore radius
t	Time
t_{Dd}	dimensionless time
t_n	Normalized time
T_{sc}	Temperature at standard condition
X_i	dimensionless term
z	real gas deviation factor, dimensionless
ϕ	Porosity
λ	Carters Drawdown Parameter
μ	Gas Viscosity

CHAPTER 1. PROBLEM STATEMENT

The increased interest and demand of the unconventional gas reservoirs to supply the United States with hydrocarbons created new challenges for resource exploration and development. Because of the ultra-low permeability and the nature of the shale formations, it is necessary to hydraulically fracture almost every well to achieve economical production. The technology of multi-stage hydraulic fracturing and horizontal drilling has provided access to the gas stored in these formations allowing a commercial amount of the gas to be produced. This increased interest in shale gas production requires a better understanding of the production behavior and a reliable technique that can help in predicting a long-term production performance. Many challenges present themselves when production is being forecasted in ultra-low permeability unconventional reservoir systems. One of the major challenges is the lack of understanding of the interaction among the fluid flow, the hydraulic fracturing, and the reservoir characteristics in these complex systems. Therefore, the production performance of the shale gas wells over the longer time periods have not been established.

A familiar technique for predicting the future production rates, when the only available data are past production rates, is Decline Curve Analysis (DCA). DCA is an empirical technique that is used for analyzing declining production rates and forecasting the future production rates for oil and gas wells. DCA has been found to successfully predict the future production rates for conventional gas wells that typically produce under boundary dominated flow (pseudo-steady state) against constant bottomhole flowing pressure. However, the application of DCA usually yields invalid production rates and the reserves in the unconventional reservoirs. Shale Gas reservoirs differ from conventional reservoirs in term of production behavior that is why conventional DCA cannot be used to predict production performance, particularly over more extended time periods. Several DCA methods have been proposed for shale wells but their application remain problematic. Furthermore, a procedure has been proposed to adjust the conventional DCA prediction for shale gas wells. However, the application of this techniques is cumbersome and requires additional information that may not be available. Therefore, a reliable and yet easy to apply predictive tool for accurate prediction of the production performance of the Marcellus horizontal shale gas wells is needed.

Chapter 2. Background

Shale is a fine-grained organic-rich sedimentary rock that is considered to be both the source rock and the reservoir. Shale reservoir is a complicated naturally fractured rock that has an insufficient matrix permeability and is usually referred to as unconventional reservoir. Shale gas is a natural gas that is either stored in the natural fractures and the pore spaces, or is adsorbed in the organic material. Multi-stage hydraulic fracturing and horizontal drilling have allowed a commercial amount of gas to be produced from shale.

Decline Curve Analysis (DCA) is a familiar technique that is used to predict a future production rate for gas reservoirs. Especially when the only available data are production rates. Decline Curve Analysis (DCA) is a reservoir engineering empirical technique that is used for analyzing declining production rates and generating a forecast of future production performance for oil and gas wells by extrapolating time-rate production data. There are a number of models for decline curve analysis that have been developed to predict the production performance, they are discussed below.

2.1. ARPS Decline Curves

The first scientific forecasting technique approach was proposed by Arps (1945). He developed a set of empirical type curves for oil reservoirs. Arps presented three types of production declines employing rate–time relationship: Exponential, Hyperbolic, and Harmonic. The decline curve fitting can be implemented on the wells producing under constant bottomhole flowing pressure and has a long production history. Arps introduced a comprehensive set of equations defining these three types (Arps 1945):

$$q = q_i(1 + bD_i t)^{\frac{-1}{b}} \qquad (2.1.1)$$

Where: q_i = Initial stabilized rate

b = Arps hyperbolic parameter theoretically between 0 and 1

D_i =Initial decline rate of the function

Where the empirical relationship for D_i is:

$$D_i = \frac{q_i}{N_{pi}} \qquad (2.1.2)$$

N_{pi} is the cumulative oil production to a hypothetical reservoir pressure of *0* psi.

Arps equations results in an exponential decline when *b = 0*, for *b = 1*, it is a harmonic and for *0<b<1*, it is a hyperbolic decline. The value of *b* can indicate the reservoir type and the derive mechanism.

Arp's method is considered to be the most straightforward decline curve technique used in the industry for conventional reservoirs producing under boundary dominated flow. Figure 1 illustrates Arps' three types of decline curve and their equations.

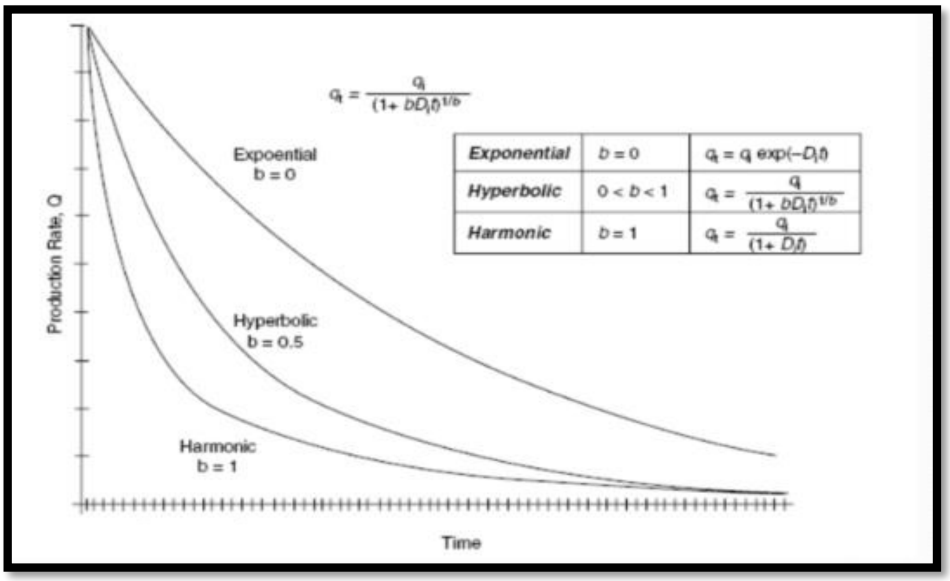

FIGURE 1. THREE TYPES OF DECLINE AND THEIR EQUATIONS (AFTER ARPS 1945)

2.2. FETKOVICH TYPE CURVES

Fetkovich used Arps' curves to develop a mathematical derivation by binding them to the pseudo- steady state inflow equation. His technique showed that certain declines were caused by physical reasons, it also allowed to calculate the reservoir properties such as permeability and skin. Fetkovich was the first to use analytical type curve to match the production data. His plots can even be related to the behavior of unconventional well production data. Fetkovich recognized that Arps decline curve analysis could only be applied under boundary dominated flow. Fetkovich was the first one to introduce the application of the type curves for production forecasting under transient flow using analytical flow equations. He developed a set of type curves for gas wells producing against constant back pressure using an empirical model.
Fetkovich (1980) proposed that:

$$q(t) = \frac{J(p_i - p_{wf})}{e^{\frac{q_i}{N_{pi}}-t}} \qquad (2.2.1)$$

Where: $J = {}^{q_i}/_{p_i}$ (2.2.2)

And: $N_{pi} = \frac{\pi(r_e^2 - r_w^2)\phi c_t h p_i}{5.615 B_{oi}}$ (2.2.3)

With the assumption that bottomhole flowing pressure (p_{wf}) is zero, it reduces to Arps equation which is:

$${}^{q_t}/_{q_i} = e^{\frac{q_i}{N} - t} \qquad (2.2.4)$$

Combining Arps equation with the pseudo-steady-state inflow equations, Fetkovich proposed that $D_i = q_i / N_{pi}$

and

$t_{Dd} = (q_i / N_{pi}) * t$.

Assuming a circular reservoir and pseudo steady inflow, Fetkovich (1980) proposed that:

$$q_{imax} = \frac{khp_i}{141.2\mu_i B_{oi}\left[\ln(\frac{r_e}{r_w} - 0.5\right]} \qquad (2.2.5)$$

$$t_{Dd} = \frac{0.00633kt}{\phi\mu c_t r_{wd}^2 \frac{1}{2}\left[\left(\frac{r_e}{r_{wa}}\right)^2 - 1\right]\left[\ln\frac{r_e}{r_{wa}} - 0.5\right]} \qquad (2.2.6)$$

t_{Dd} is a dimensionless time and:

$$q_{Dd} = \frac{\mathrm{q(t)}}{\mathrm{qi}} \qquad (2.2.7)$$

Plotting dimensionless time vs. dimensionless q will results in classic Fetkovich decline curves. Fetkovich combined the constant-pressure analytical solutions and the standard "experimental" exponential, hyperbolic, and harmonic decline curve solutions on the above dimensionless curve as illustrated in Figure 2. The analytical and empirical solutions share the exponential decline in both. Fetkovich noted that analyzing the rate data available only in the transient period of the constant terminal pressure by empirical Arps, a much greater values than *1* of *b* would be required to fit the data.

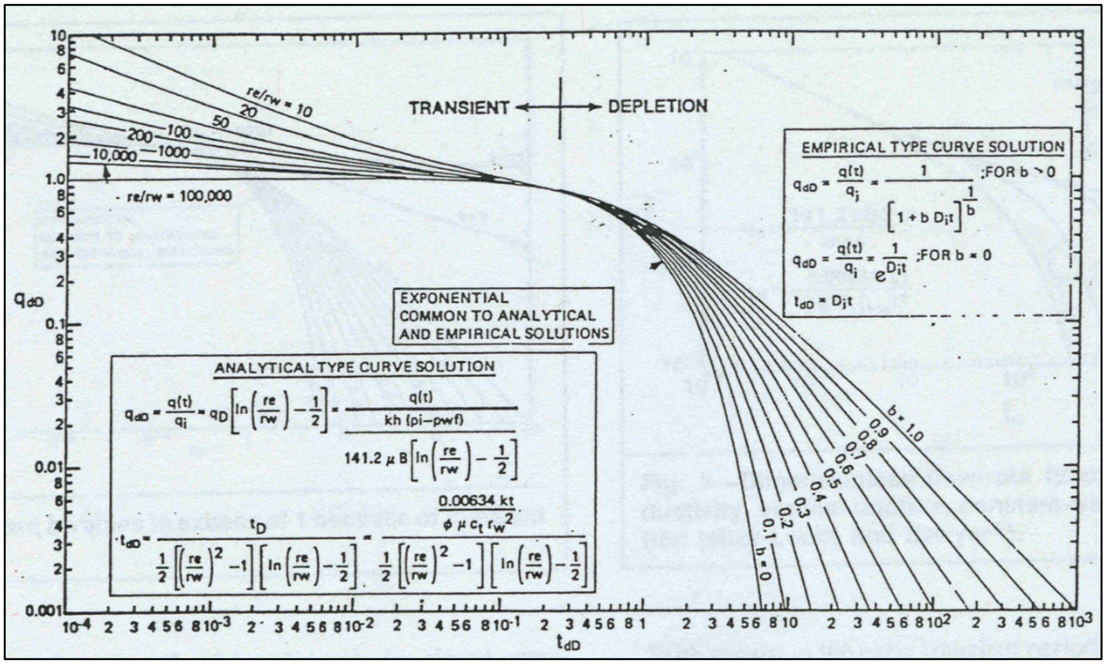

FIGURE 2. FETKOVICH TYPE CURVES (AFTER FETKOVICH 1980)

2.3 Carter Type Curves

Fetkovich did not take into account the dependency of gas properties on pressure. Fetkovich type curves generated to be used for liquids. Carter introduced another set of type curves that can be used to forecast gas production rates. Carter used a finite-difference reservoir model to show that the pressure impacted the type curves during the pseudo-steady state flow due to the dependency of gas properties on the pressure. Carter used the variable, λ, for gas compressibility. Carter (1981) defined λ as:

$$\lambda = \frac{\mu_{gi} c_{gi}}{2} \frac{m(p_i) - m(p_{wf})}{(^{p}/_{z})_i - (^{p}/_{z})_{wf}} \qquad (2.3.1)$$

μ_{gi} *and* c_{gi} are the gas viscosity and compressibility at the initial pressure. Values of have λ their own set of decline curve stems. Figure 3 is a plot for a dimensionless rate vs time on a log-log scale, represent the radial flow type curve for an ideal gas flow solution for $\lambda = 0.75$

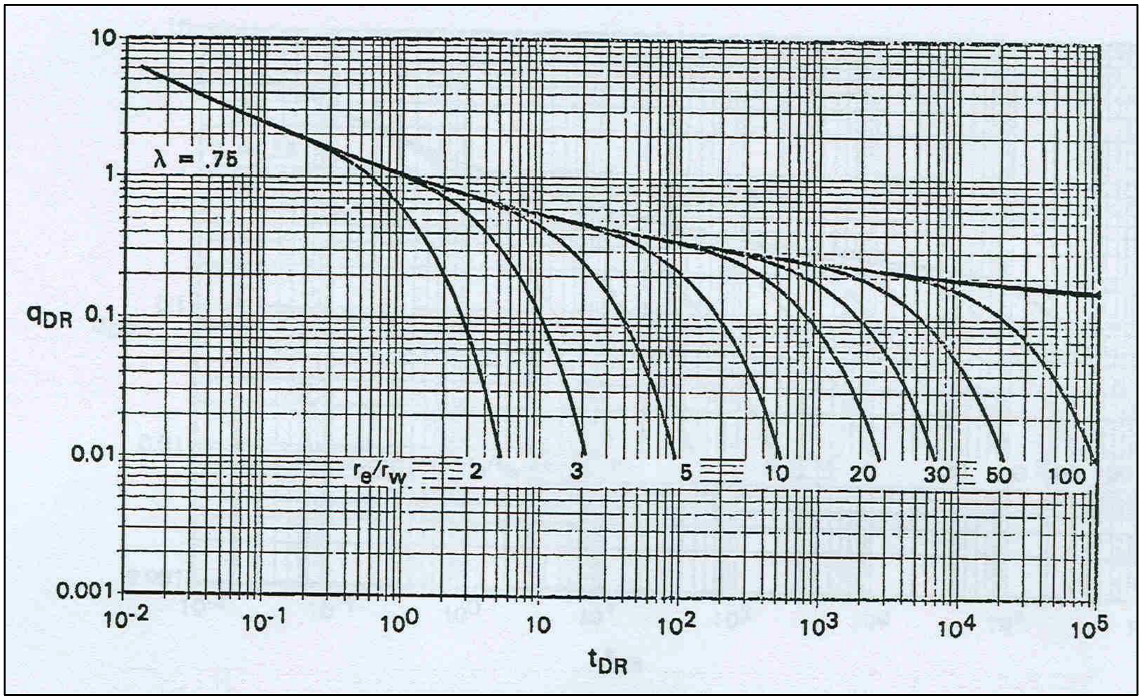

FIGURE 3. TYPE CURVES FOR GAS SYSTEMS (AFTER CARTER 1981)

2.4 Fraim and Wattenbarger Type Curve

The effect of gas properties on the behavior of the gas production decline has also been explained by Fraim and Wattenbarger. They identified the concept of pseudo-time to analyze gas well production data by developing the concept of pressure transient analysis from Fetkovich (1980) and Carter (1981). Fraim and Wattenbarger derived an equation for bounded, radial gas reservoirs:

$$\ln\left(\frac{q}{q_i}\right) = \frac{-2J_g\left({}^{p}/_{z}\right)_i}{G\left(\mu_g c_g\right)_i}\int_0^t \frac{\left(\mu_g c_g\right)_i}{\overline{\mu}_g \overline{c_g}}\,dt \qquad (2.4.1)$$

Where

$$J_g = \frac{1.9875E^{-5}k_g h}{0.5\ln\left(\frac{2.2458A}{C_A {r_w}^2}\right)}\frac{T_{sc}}{P_{sc}T} \qquad (2.4.2)$$

Fraim and Wattenbarger modified Fetkovich decline curves variables to include normalized time and the area of general reservoir shape. Fraim and Wattenbarger defined pseudo-time as:

$$t_n = (\mu c_t)_i \int_0^t \frac{dt}{\mu c_t} \qquad (2.4.3)$$

They used the values of the circular reservoirs shape factor (C_A) as *19.1795* instead of *31.62*, Thus:

$$q_{dD} = \frac{q_g p_{sc} T \, {}^{1}\!/_{2} \ln\left(\frac{2.2485A}{19.1785 r_w^2}\right)}{1.987\times10^{-5} T_{sc} k_g h \left(p_{pi} - p_{pwf}\right)} \qquad (2.4.4)$$

and

$$t_{dD} = \frac{\frac{0.00633 k_g t_n}{(\emptyset \mu c_t)_i r_w^2}}{{}^{1}\!/_{2}\left(\frac{A}{\pi r_w^2} - 1\right) \ln\left(\frac{2.2485A}{C_A r_w^2}\right)} \qquad (2.4.5)$$

Figure 4 and Figure 5 were simulated to explain the use of the normalized time. The production rate was plotted agaisnt time and each figure shows three curves, the analytical solution for the exponental decline case (*b* = *0*) is represented by the solid line, the transient behavior is represented by the earleir flat part. The traingles represent the simulated results plotted as actual time, and the squares represent the normalized time. The figures confirms that with liquid solutions the normalized time can be analyzed by Fetcovich's type curves (*b* = *0*), since the normalized time trasformation overlaps the analytical solution in the boundry flow dominated. The actual time that was represented by the traingles do not match the Fetkovich type curve for any value of *b*. This indicates that a closed gas system does not follow an exponentail, hyperbolic, or harmonic decline curve.

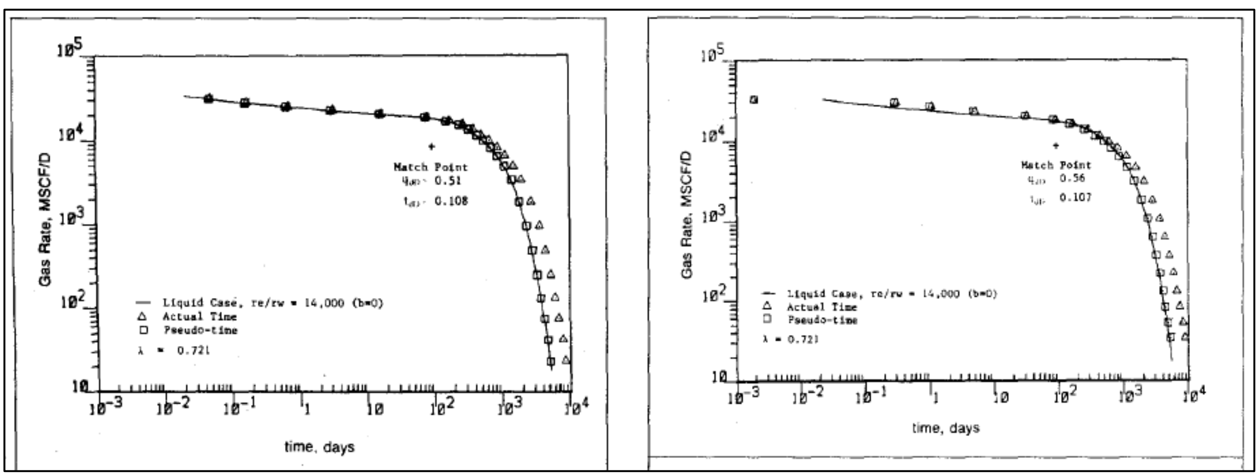

FIGURE 4. THE EFFECT OF GAS COMPRESSIBILITY AND GAS VISCOSITY ON A RATE-TIME DECLINE CURVE (AFTER FRAIM AND WATTENBARGER 1987)

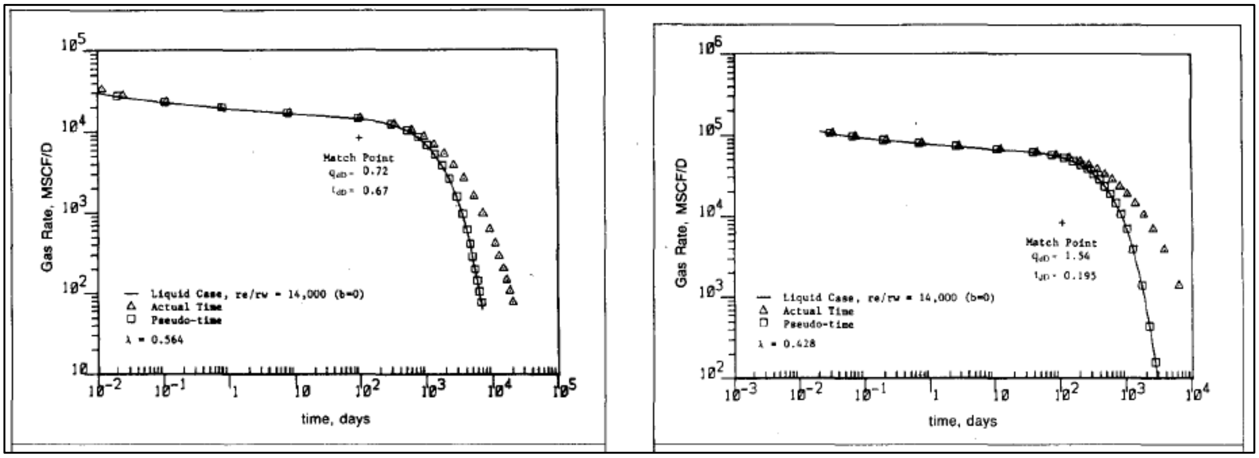

FIGURE 5. THE EFFECT OF GAS COMPRESSIBILITY AND GAS VISCOSITY ON A RATE-TIME DECLINE CURVE (AFTER FRAIM AND WATTENBARGER 1987)

The effect of non-Darcy flow in developing these type curves was neglected by both Carter and Fraim and Wattenbarger. The work of Fraim and Wattenbarger (1987) and Palacio and Blasingame (1993) was an improvement on Fetkovich. Using the pseudo-time, they developed a correlation of the gas and liquid flow solutions that accounted for the change in gas properties over time. This approach allowed DCA to be applied to gas reservoirs. In addition, Palacio and Blasingame's presented a "Fetkovich-Carter" type curve. Which incorporates the constant pressure gas flow solution and the Arps' decline curve stems on a single type curve. Plotting Blasingame's type curves, the analytical exponential stem of Fetkovich becomes harmonic. They developed a material balance time that allowed for more accurate match to the production data. In fact, their material balance time showed that a constant pressure depletions can be treated as a constant rate depletion. That was important in the field of pressure transient analysis that focused on the analytical model for constant rate data which are more effective in determining the flow regimes and reservoir properties than decline curve analysis.

2.5 AMINIAN TYPE CURVE

Aminian combined the quadratic gas flow equation (Eq 2.5.1) with the material balance equation (Eq 2.5.2) for gas reservoir to account for both the non-Darcy flow and the effect of pressure on the gas properties.

$$P_p(\bar{P}) - P_p(P_{wf}) = aq + bq^2 \qquad (2.5.1)$$

$$\frac{P}{Z} = -\left(\frac{P_i/Z_i}{G}\right)G_p + \frac{P_i}{Z_i} \qquad (2.5.2)$$

An analytical solution was derived to understand the decline behavior of gas wells flowing under the Pseudo-steady State condition:

$$\ln q_D + 2(1 - F_{NDi})(q_D - 1) + \frac{F_{NDi}F_{taD}}{\left[1 - (^1/_{X_i})\right]\lambda} t_D = 0 \qquad (2.5.3)$$

where:

$$q_D = {}^{q}/_{q_i} \qquad (2.5.3)$$

$$t_D = {}^{q_i t}/_{G_i} \qquad (2.5.4)$$

$$F_{NDi} = 1 + \left({}^{b}/_{a}\right) q_i \qquad (2.5.5)$$

$$X_i = {}^{\left(\overline{p}/_{z}\right)_i} \Big/ {}_{(\overline{P}/_{z})_{wf}} \qquad (2.5.6)$$

and

$$F_{tad} = \frac{\mu_i C_{gi}}{t} \int_0^t \frac{dt'}{\mu C_g} \qquad (2.5.7)$$

Aminian quantified the non-Darcy flow effect by F_{NDi}. The effect of pressure on gas properties is represented by F_{tad} (Lee et al) and $\lambda\ Eq(2.3.1)$.

Ignoring both non-Darcy flow and pressure effect (i.e., F_{NDi}=1, $\lambda = 1, and\ F_{tad} = 1$), Eq (2.5.3) will be reduced to exponential decline as proved by Fetkovich. Ignoring only the non-Darcy flow where F_{NDi}=1, Eq (2.5.3) will be reduced to Material Balance Time as shown by Fraim and Wattenbarger. Aminian et al generated the following type curves using equation (2.5.3). Figure 6 represent a set of type curves for P_i *=2000 psia* and $F_{NDi} = 2$, generated for different value of X_i. Figure 7 shows that for different values of F_{NDi}, the shape of the curve will change for $\boldsymbol{X_i} = \infty$

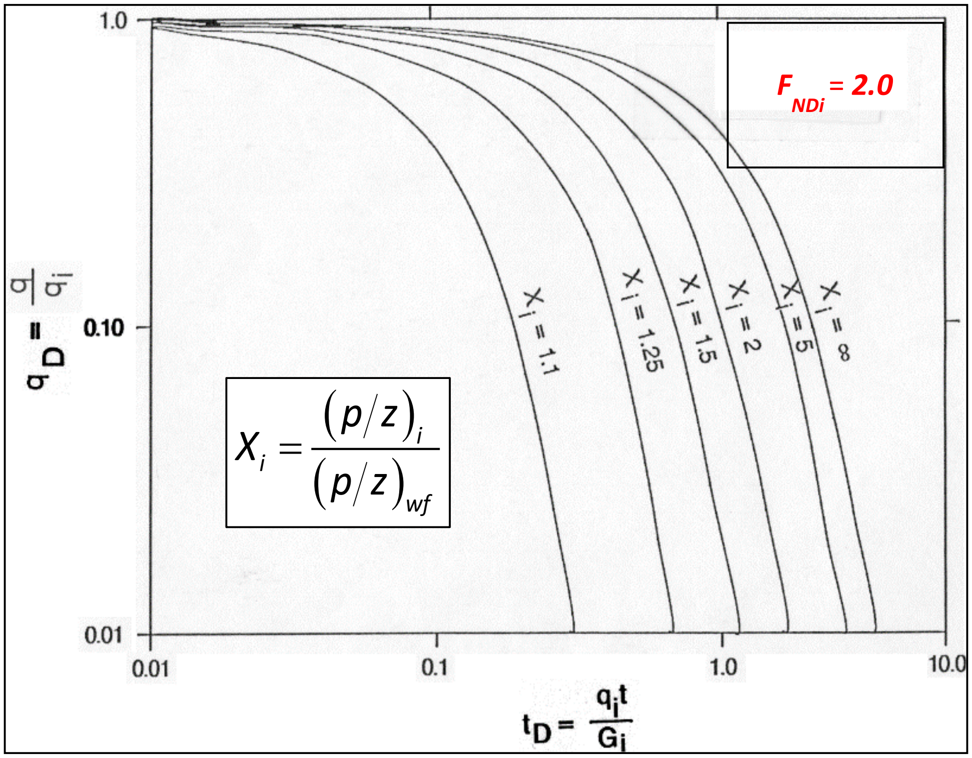

FIGURE 6. CONSTANT BACK-PRESSURE GAS-WELL PRODUCTION-DECLINE CURVES P=2000 PSI (AFTER AMINIAN ET AL 1990)

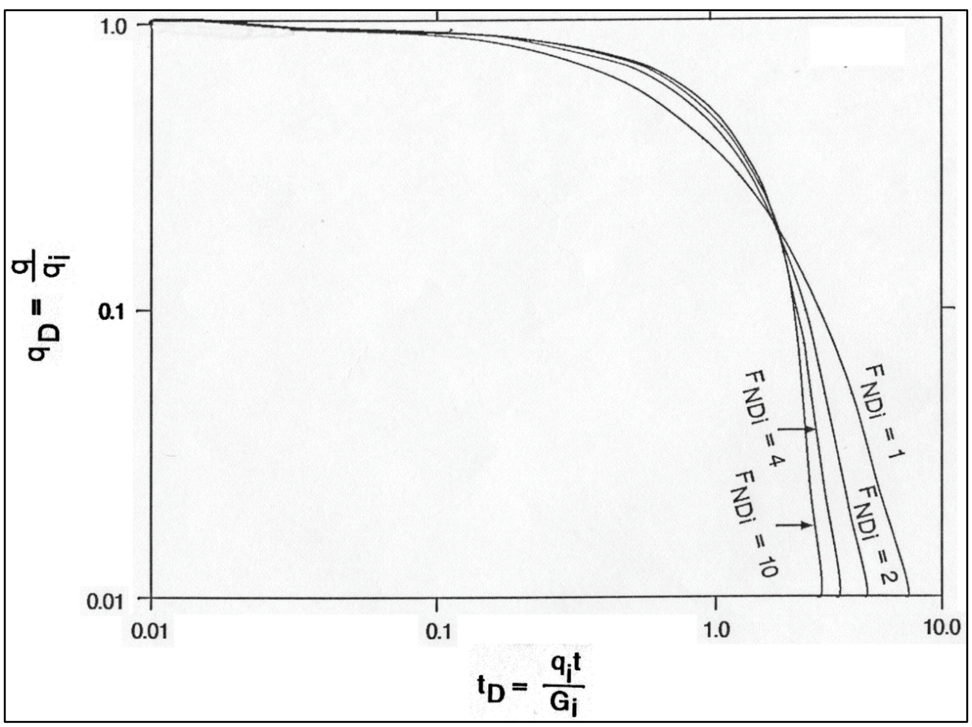

FIGURE 7. EFFECT OF NON-DARCY FLOW TYPE CURVES X_i =∞ (AFTER AMINIAN 1990)

It was noted that finding a unique match is not always simple if the available data are limited and the production history falls under the early part of the decline curves.

2.6 Shale Gas Analysis Techniques

In order to apply DCA and achieve a best fit of the existing flowrate trend the following list of assumptions adapted from Lee and Wattenbarger (1996) must be considered:

- The future production trend is governed by the history of the production data and by whatever trend is resulted from extrapolating of a curve (i.e. rate-time model) or mathematical relationship.
- Current production rate, operating conditions, and field development will continue without considerable changes that may affect the model extrapolation into the future.
- The well is producing under boundary dominated flow.
- The well is producing under constant bottomhole flowing pressure.

Conventional reservoir systems are often produce under the above conditions however; Shale Gas reservoirs differ from conventional reservoirs in term of production behavior that is why Conventional Decline Curve Analysis cannot be used to predict production performance, particularly over longer time periods.

Since unconventional gas shale reservoirs exhibit a transient flow regime, applying the conventional Arps decline curve usually yields to over-estimating the production rates. Thus, several modifications to Arp's model have been developed.

2.6.1. Terminal / Limited Decline Rate

The concept of the limited decline rate is to start with the hyperbolic decline curve and transitioning into an exponential decline curve at specified limiting effective decline rate. The decline curve at any time can be calculated as:

$$D = \frac{-\Delta q / q}{\Delta t} \qquad (2.6.1.1)$$

The time at which the decline changes from hyperbolic into exponential decline rate, can be calculated as:

$$t = \frac{(\frac{Di}{Dexp} - 1)}{bDi} \qquad (2.6.1.2)$$

This approach can be effective to predict the production performance if used carefully. However, it is a non-unique approach that can result in extremely different estimates of reserves with time, and/or steady estimates.

2.6.2. Power Law Decline

The power law decline was introduced by Ilk et al. (2008) as an alternative to Arps exponential decline to predict the reserves in tight gas reservoirs by combining the loss ratio defined below with the hyperbolic rate decline.

Loss Ratio: $D = D_\infty + nD_i t^{n-1}$ (2.6.2.1)

Rate-time relation

$q(t) = q_i e^{(-D_\infty t - \frac{D}{n} t^n)}$ (2.6.2.2)

where:

q_i= rate "intercept" at $t = 0$

D_∞= decline constant at infinite time

D_i = decline constant.

D_1 = decline constant "intercept" at 1-time unit.

n = time exponent.

2.6.3. Stretched Exponential Production Decline (SEPD)

Valkó and Lee (2010) modified the traditional Arps method to be more suited for the unconventional reservoirs. This decline curve gives more realistic prediction for low-permeable wells with long-duration transient flow. Table 1 shows the Stretched Exponential Production Decline Model definitions and expressions. SEPD model has 3 factors: n is the exponent, τ is the characteristic number of periods, and q_i is the initial production rate

TABLE 1. STRETCHED EXPONENTIAL PRODUCTION DECLINE MODEL, (AFTER VALKÓ AND LEE 2010).

$\frac{dq}{dt} =$	$-n\left(\frac{t}{\tau}\right)^n \frac{q}{t}$	Defining differential equation of the model
$q =$	$q_0 \exp\left[-\left(\frac{t}{\tau}\right)^n\right]$	Rate expression as function of time
$Q =$	$\frac{q_0\tau}{n}\left\{\Gamma\left[\frac{1}{n}\right] - \Gamma\left[\frac{1}{n}, \left(\frac{t}{\tau}\right)^n\right]\right\}$	Cumulative production as a function of time
$\text{EUR} =$	$\frac{q_0\tau}{n}\Gamma\left[\frac{1}{n}\right]$	EUR in terms of the model parameters
$rp = 1 - \frac{Q}{\text{EUR}} =$	$\frac{1}{\Gamma\left[\frac{1}{n}\right]}\Gamma\left[\frac{1}{n}, -\ln\frac{q}{q_0}\right]$	Recovery potential calculated from actual rate using two model parameters

2.6.4. Duong Decline Method

Duong Decline Method (2010) designed for fractured unconventional reservoirs. The decline curve is fitted for wells that exhibit long periods of transient flow

$q = q_1 t(a, m) + q_\infty$ (2.6.4.1)

q = flow rate, volume/time

$a = vertical\ axis\ intercept\ of$ $\log\frac{q}{Gp}$ vs t.

$m = slope\ of\ log - log\,\frac{q}{Gp} vs\ t$

$Gp = cumilative\ gas\ production.$

Duong's original model works well to predict the production forecast for shale gas reservoirs that have a short production history and assumes to be under a transient flow, it usually over-estimate the recovery for wells that produce under a boundary dominated flow. (Joshi and Lee, 2013).

2.6.5. Modified Duong's Model

Joshi and Lee (2013) adjusted Duong's original model to be more suitable for wells that have longer production history and exhibits a boundary dominated flow (BDF). Joshi and Lee suggested that for wells that have a production history less than 18 months, forcing the regressed line through the origin ($q_\infty = 0$) will limit the error in estimating remaining production. Also to account for later boundary flow, Joshi and Lee suggested to switch from Duong to Arps at a specified time since Duong model was designed to model only transient flow. Figure 8 shows the difference between using q_∞ for a Barnett shale well with matches of production history and when setting $q_\infty = 0$. The Plot on the right shows more realistic forecast.

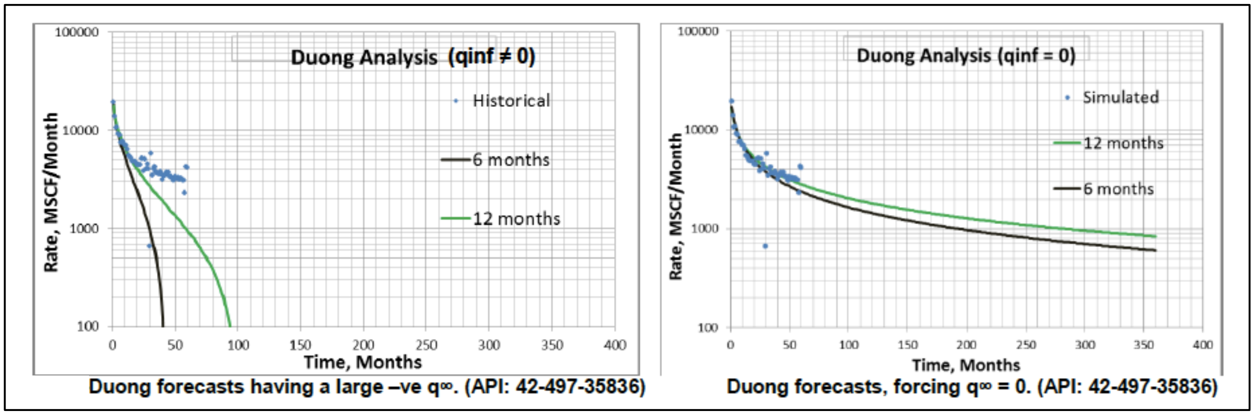

FIGURE 8. MODIFIED DUONG MODEL RESULTS (AFTER JOSHI AND LEE 2013)

As mentioned previously all the above models were developed to prevent over estimating the reserves for Arps DCA, however reliable predictions cannot be achieved using these models unless the production history include both transient and boundary dominated flow data. And none of these equations can be considered reliable for production forecasting for all unconventional reservoirs due to operation conditions and the production behavior of the rate time equations.

2.7. Production Performance for Horizontal Wells with Multiple Hydraulic Fractures

The flow regimes and the production behavior of the horizontal wells have been studied by multiple of investigators; Lu et al (2009) concluded that depending on the reservoir parameters, number of flow behavior can be presented and one or more could be masked or missing. In the early production period and for a short time a radial flow in vertical direction exist. Then an intermediate linear behavior develops due to the length of the horizontal well which is greater than the formation thickness. Afterward a transition flow dominates the production behavior and finally a late period flow is observed. The concept of trilinear flow for hydraulically fracture reservoirs was introduced by Ozkan et al (2009) and Brown et al (2009), they pointed out that the flow is mostly linear perpendicular to the hydraulic fracture and that the contribution of micro-Darcy formation past the stimulated volume is negligible. The trilinear flow couples three linear flow regions including the hydraulic fracture, the inner area between the fractures, and the area past the tip of the fracture. Belyadi, A. et al (2010), Belyadi, F. et al (2012), and Joshi and Lee (2013) also concluded that the flow regimes include the initial radial-linear fracture flow which occurs in hydraulic fracture plane and has a characteristics similar to wellbore storage, that is due to the high conductivity of the hydraulic fracture, then the formation linear flow which is the most commonly flow period related to the hydraulic fractures, the fracture interference flow, the linear flow in unstimulated matrix (tri-linear flow), and the boundary dominated flow (BDF).

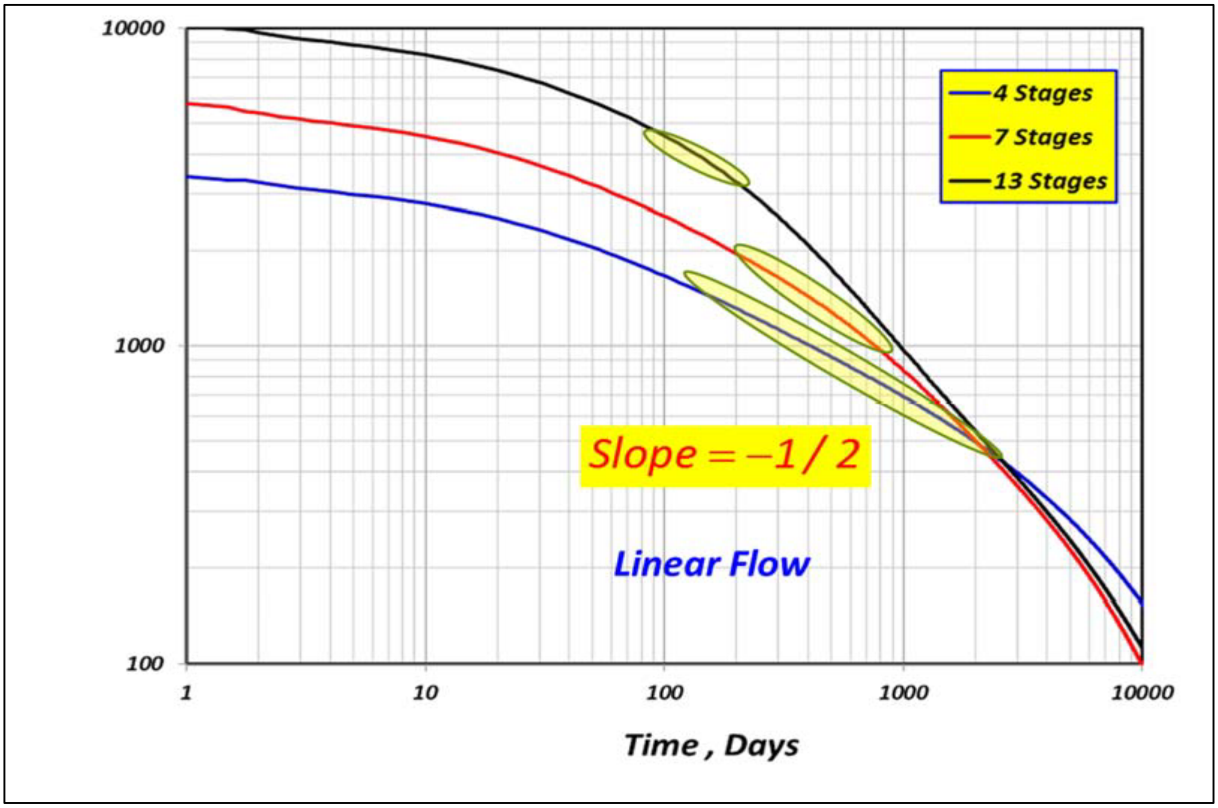

FIGURE 9. PRODUCTION RATES FOR DIFFERENT NUMBER OF STAGES (4000×2000) (AFTER BELYADI 2012)

Figure 9 shows that several slopes with different values are present. This might indicate that different flow periods may be present. The early period of 10 to 70 days has a slope of nearly -4, the second flow period reflects a slope of nearly -2, and the slope of last part of all the production profiles is -1 due to the boundary effects. Earlier period showed bi-linear and linear effects. To obtain a better understanding of the production behavior, the derivative of the inverse of the flow rate (*1/q*) was plotted against time on log-log scale as illustrated in Figure 10.

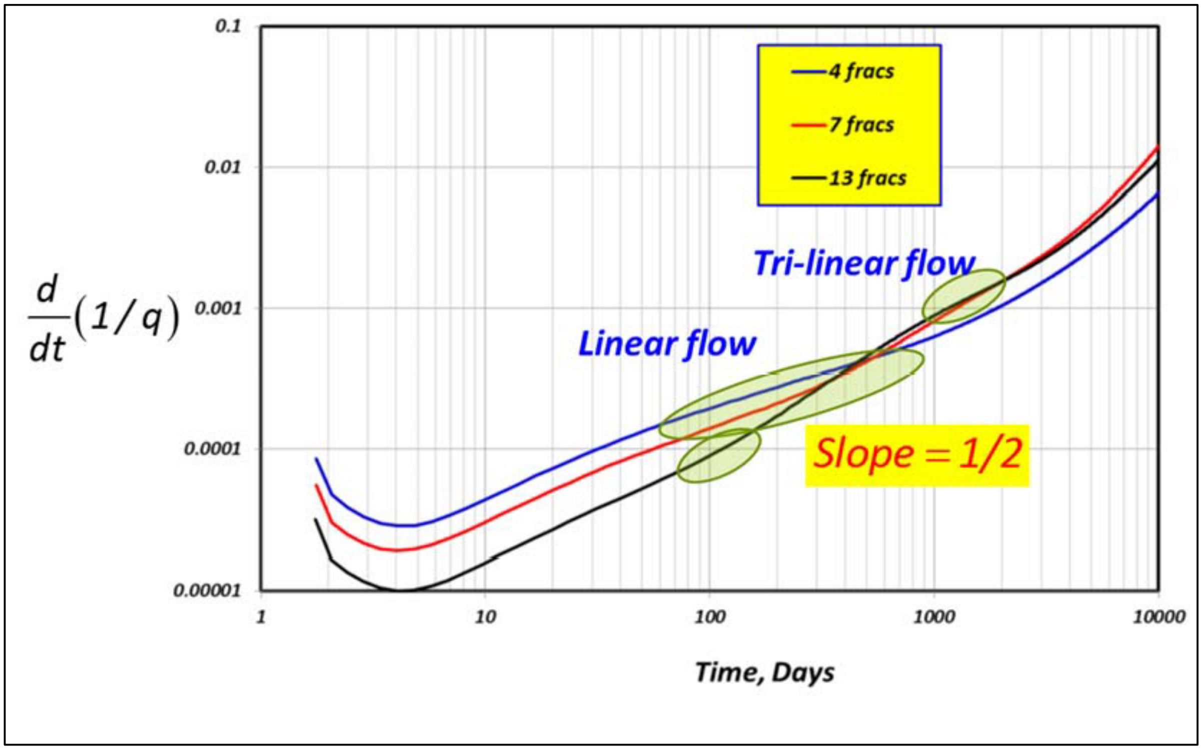

FIGURE 10. DIAGNOSTIC PLOT OF DERIVATIVE OF 1/q AGINST TIME (AFTER BELYADI 2012)

After investigating Figure 10, they concluded that the early period is not under the bi-linear flow as the slope was not equal to -¼. In fact, it is the radial-linear flow. However, the linear flow was presented in the case with 4 and 7 frac stages only as the slope was equal to ½. Finally, the last production periods have the slope of 1. The case with 13 frac stages resulted in two separate periods with the slope 1. This may be due to presence of the different boundaries. The first is due the interference between the stages and second is due to the impact of the reservoir exterior.

Belyadi, F. et al (2012) provided an insight into the long term production performance for horizontal wells with multiple hydraulic fractures in ultra-low permeability formations. They applied the production decline analysis to the horizontal wells with the multiple hydraulic fracture stages. In their approach, the production history was divided into several periods and each period was matched with a separate hyperbolic decline curve to estimate the values for b and D_i for each period.

Table 2 shows that the early period is resulted in b value of *2* which indicates the transient linear flow. However, the latter part shows a decline curve that is characterized by $b = 1$, which is the harmonic decline.

TABLE 2. RESULTS OF THE DECLINE CURVE ANALYSIS (AFTER BELYADI 2012)

Number of Stages	*Period, Years*	*b and Di*	*Period, Years*	*b and Di*
4	2-7	2, 2.4	14-30	1, 0.64
7	0.5-2	2, 11	6-24	1, 0.78
13	0.2-0.5	2, 53	2-20	1, 1.60

Belyadi, F. et al (2012) concluded that the approach of using a single value for the decline exponent (b) cannot provide reliable results to characterize the entire production period. This is due to the changes in flow regime. That is why conventional decline curve analysis cannot be used to predict production performance over longer time periods based on the early production data. It will only result in over predicting the production rates.

Nelson et al (2014) concluded that the production profile of the Marcellus shale well can be closely fitted to Arps, PLE and Doung decline curves. However, when the production profile is limited to the early production period, the simple extrapolation of the decline curve could lead to inaccurate or erroneous production predictions. Nelson et al (2014) developed a number of correlations to adjust the Arps, PLE and Doung decline curves constants obtained from limited production history to achieve more accurate long-term production predictions. However, the application the correlations appears to be cumbersome and limited to few cases.

CHAPTER3. OBJECTIVE AND METHODOLOGY

Marcellus Shale is an important source of natural gas located in the Appalachian Basin. Shale gas reservoirs present a unique challenge for production data analysis. The objective of this study is to develop a reliable and easy methodology to apply predictive tool in order to improve the conventional DCA for obtaining accurate prediction for the production performance.

3.1 METHODOLOGY

The following steps were implemented in this study:

A. DATA COLLECTION

Production data from a number of horizontal Marcellus Shale gas wells located in West Virginia were collected. The dataset included the daily production gas rates, the cumulative production, and time.

B. DATA ANALYSIS

The daily production data were grouped into monthly production rates. The previous investigation have indicated that the production rates follow a Harmonic Decline for long production periods. Therefore, a Harmonic Decline was applied to the entire production data to investigate the decline behavior and to find equations to match the production decline as illustrated in Figure 11. To investigate how the decline curve constants change over time, the production history was truncated at shorter time periods including 12-month, 18-month, 24-month, 30-month, etc. Then, the inverse of the monthly production ($1/q$) was plotted against time (t) for each period. The equation constants (the slope and intercept) for each period were determined. These constants were then used to predict the future production rates. As was noted previously, using the constants for the first 12-month period will result in overestimation of the production rates as shown in the Figure 12. Figures 13, 14, and 15 illustrate the similar results for 18-months, 24-month, and 30-month periods. The results of the analysis also provided the values of constants for each period.

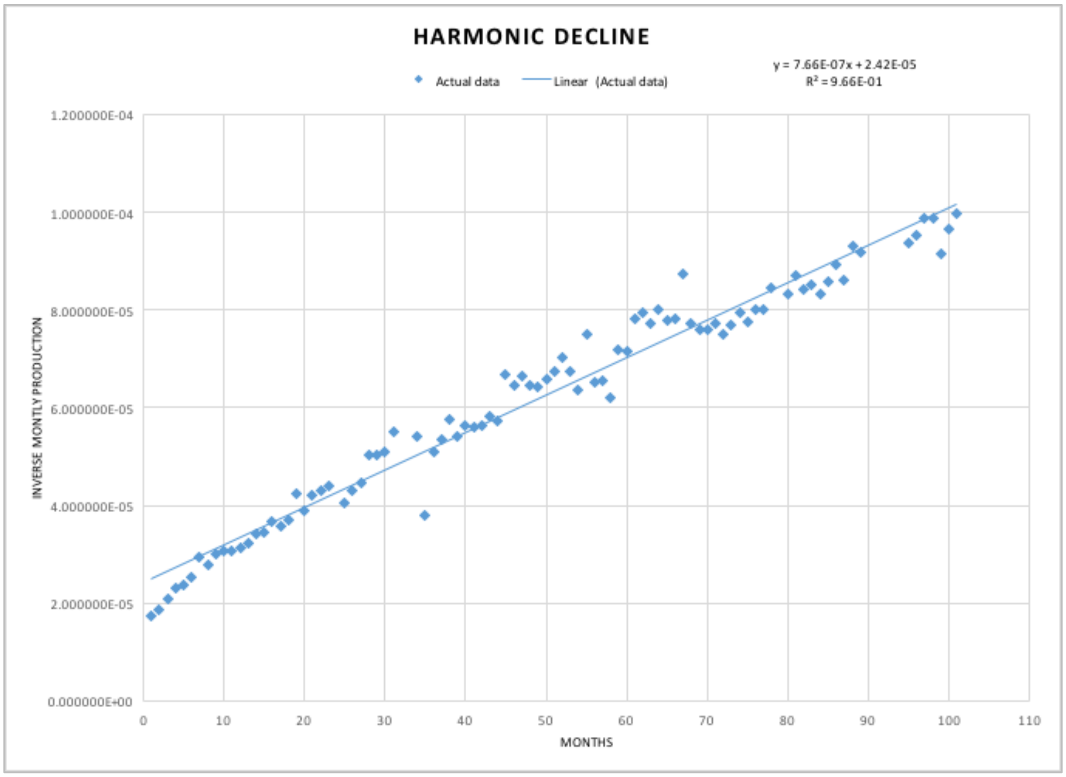

FIGURE 11. HARMONIC DECLINE FOR WELL-1

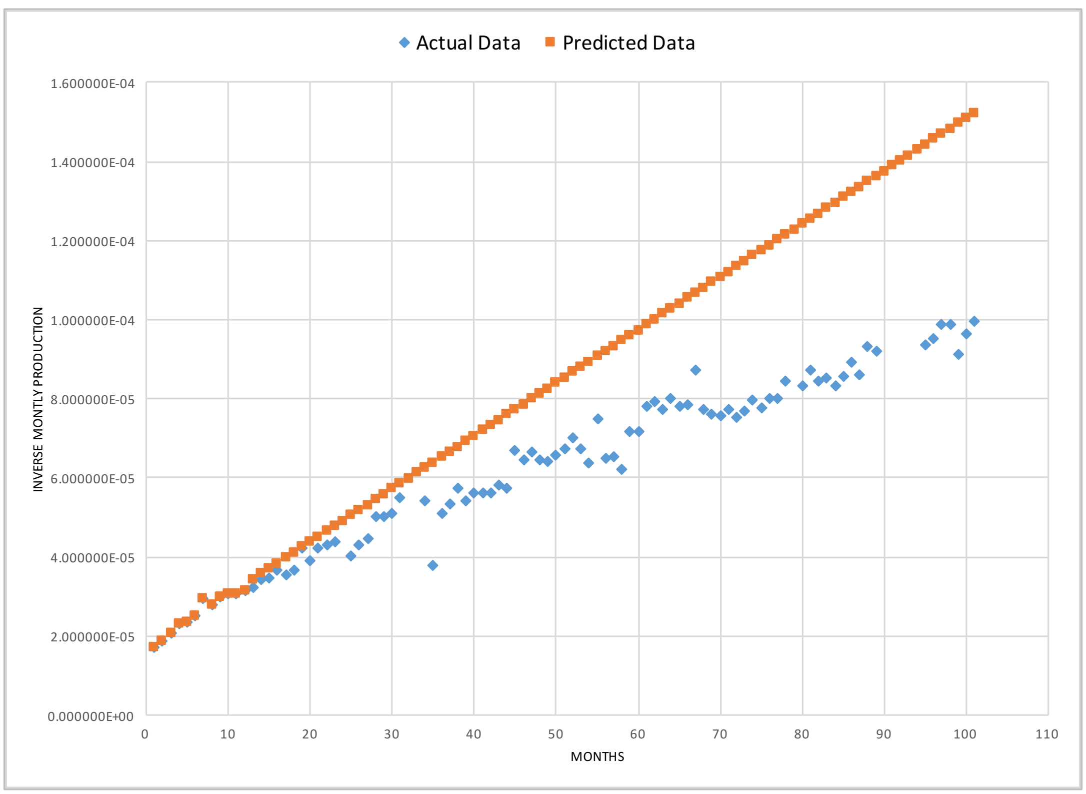

FIGURE 12. THE PREDECTED PRODUCTION RATES BASED ON 12-MOTNHS PERIOD AS COMPARED TO THE ACTUAL PRODUCTIONION RATES FOR WELL-1

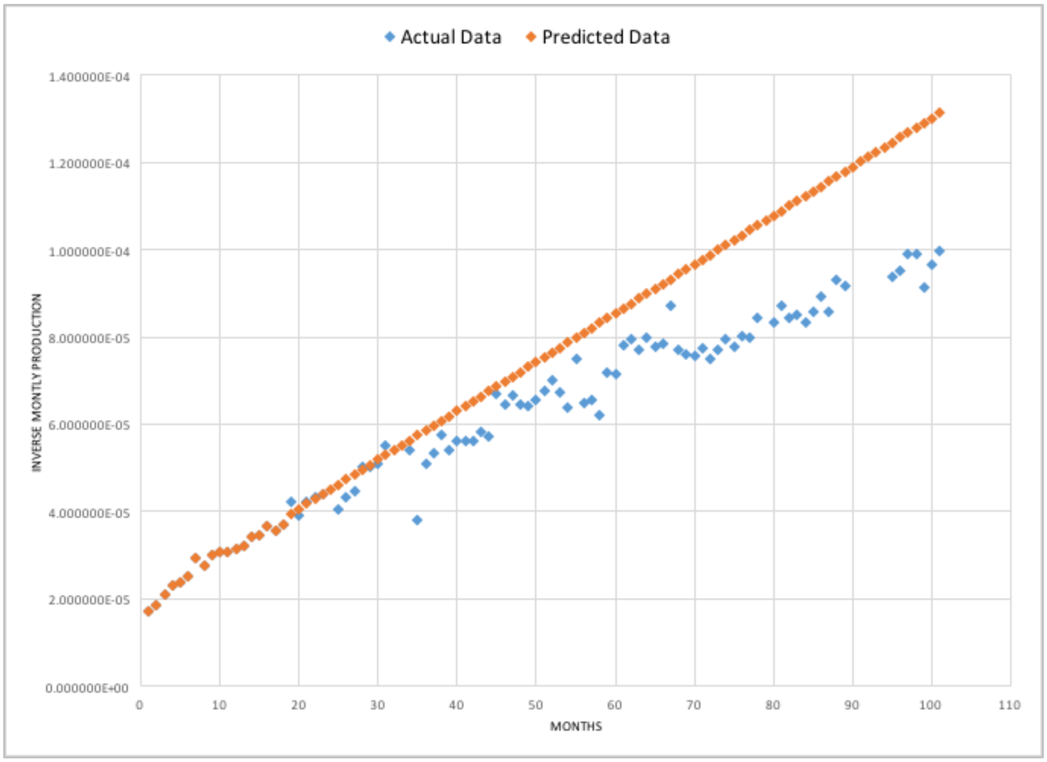

FIGURE 13. THE PREDECTED PRODUCTION RATES BASED ON 18-MOTNHS PERIOD AS COMPARED TO THE ACTUAL PRODUCTIONION RATES FOR WELL-1

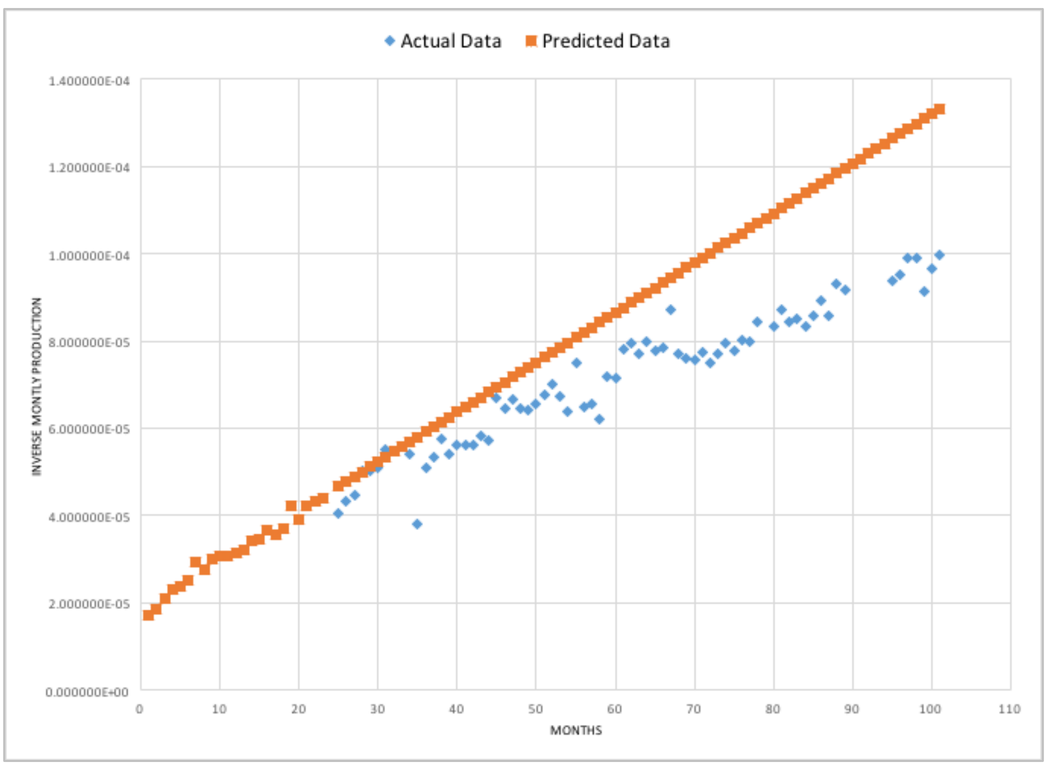

FIGURE 14. THE PREDECTED PRODUCTION RATES BASED ON 24-MOTNHS PERIOD AS COMPARED TO THE ACTUAL PRODUCTIONION RATES FOR WELL-1

C. Development of the Prediction Technique

Figure 16 compares the results of the analysis and shows that as the duration of the periods increase the predicted flow rates approach the actual data. To eliminate the noise in the data, a polynomial equation was generated to smooth the data for each well. Figure 17 illustrate the application of the Harmonic decline to the entire smoothed production data for well 1. Then, the inverse of the flow rate from the smoothed data was replotted against time for different time periods to examine the behavior of the decline and the changes in the coefficients as the duration of the periods increased. Figure 18 compares the results of the analysis for the smoothed data and shows that as the duration of the periods increase the predicted flow rates approach the actual data.

Table 3 summarizes the results of data analysis (the coefficients) as the duration of the periods increased. Figure 15 illustrate how the constants change with increasing the duration of production history. Both constants exhibit linear trends with time which can be used to adjust the constants for prediction purposes.

Table 3. Constants based on the different time periods for well-1

Months	***slope***	***Intercept***	***R^2***
12	1.0320E-06	1.9560E-05	0.973
18	9.8464E-07	1.9826E-05	0.984
24	1.0235E-06	1.9536E-05	0.989
30	9.9800E-07	1.9744E-05	0.987
36	9.6086E-07	2.0181E-05	0.986
42	9.2600E-07	2.0649E-05	0.985
48	8.9704E-07	2.1075E-05	0.987
54	8.8900E-07	2.1211E-05	0.990
60	8.7272E-07	2.1538E-05	0.991
66	8.5900E-07	2.1824E-05	0.992
72	8.3222E-07	2.2461E-05	0.990
78	8.1314E-07	2.2947E-05	0.989
84	7.9100E-07	2.3549E-05	0.987
90	7.7700E-07	2.3957E-05	0.987
96	7.6300E-07	2.4398E-05	0.987
102	7.5047E-07	2.4830E-05	0.987

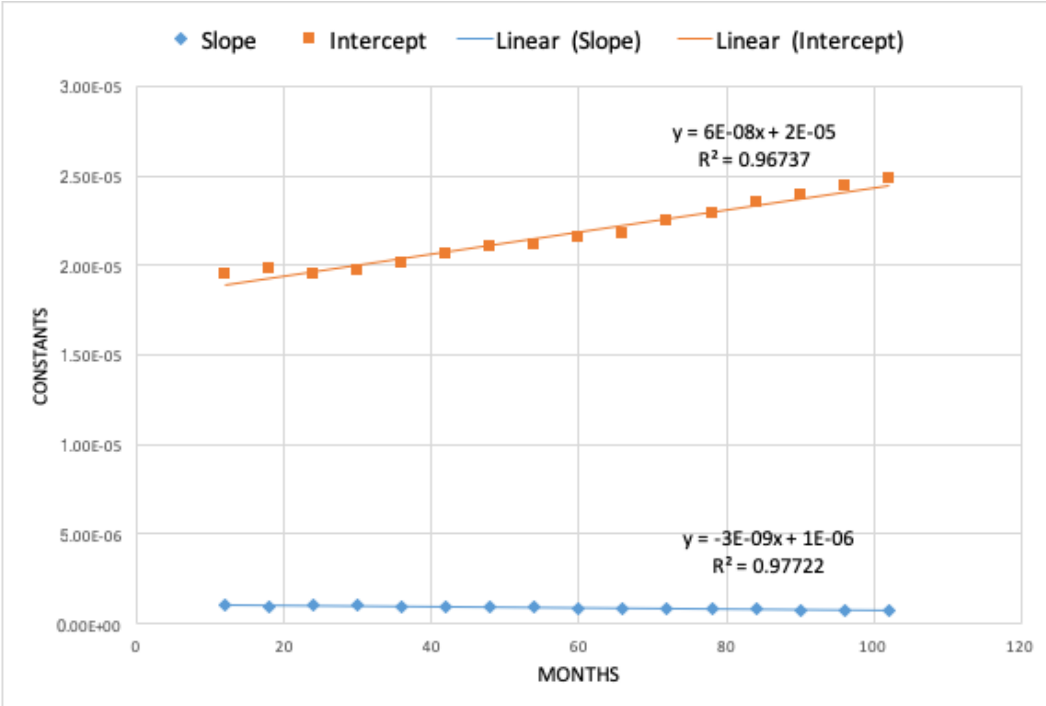

FIGURE 15. THE SLOPE AND THE INTERCEPT VS TIME

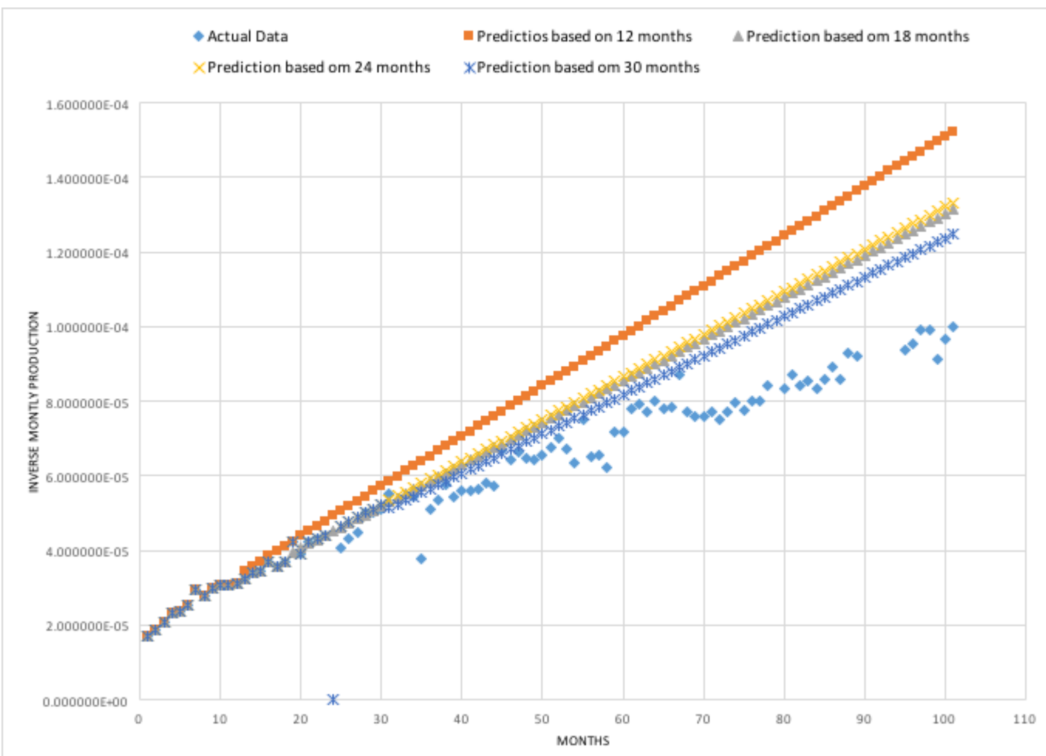

FIGURE 16. COMPARING THE PREDECTIONS FOR WELL-1

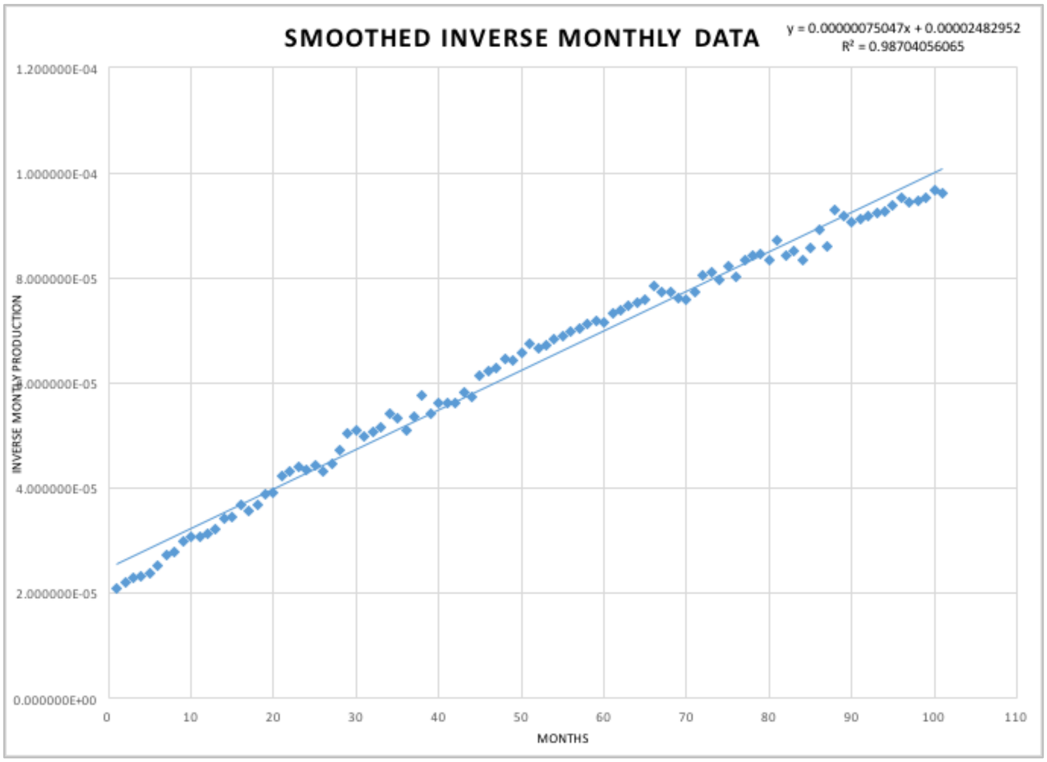

FIGURE 17. HARMONIC DECLINE FOR WELL-1SMOOTHED DATA

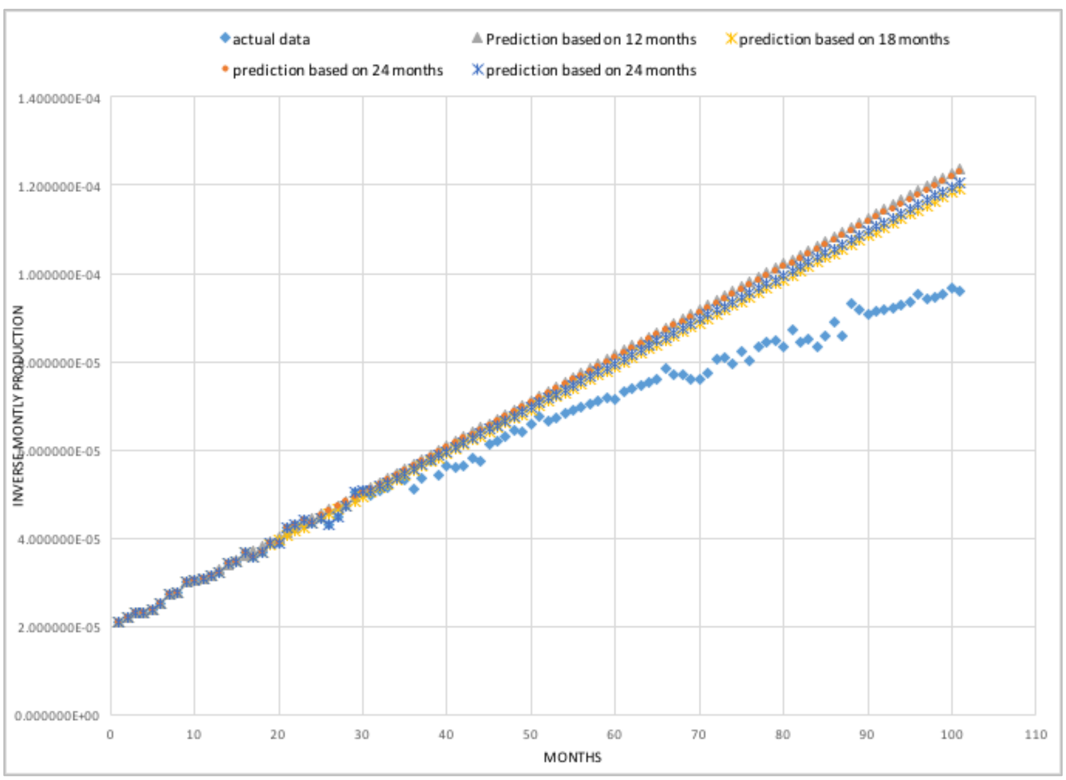

FIGURE 18. COMPARING THE PREDECTIONS FOR WELL-1 AFTER SMOOTHING THE DATA

The results of analysis clearly illustrate that the values of the constants determined based on the limited production history cannot provide reliable predictions. However, as the duration of the period increases (i.e. longer production history), the prediction improves. Furthermore, the predicted production rates immediately after the history (about the same duration as the history) are relatively close to the actual production data. Based on these conclusions, a continuously adjusting technique for prediction was developed. This procedure is based on predicting the production rates for a 6-month period at a time. Upon actual data becoming available after each 6-month period, a new prediction for the next following six months will be made. . Figure 19 illustrate the results for well 1.

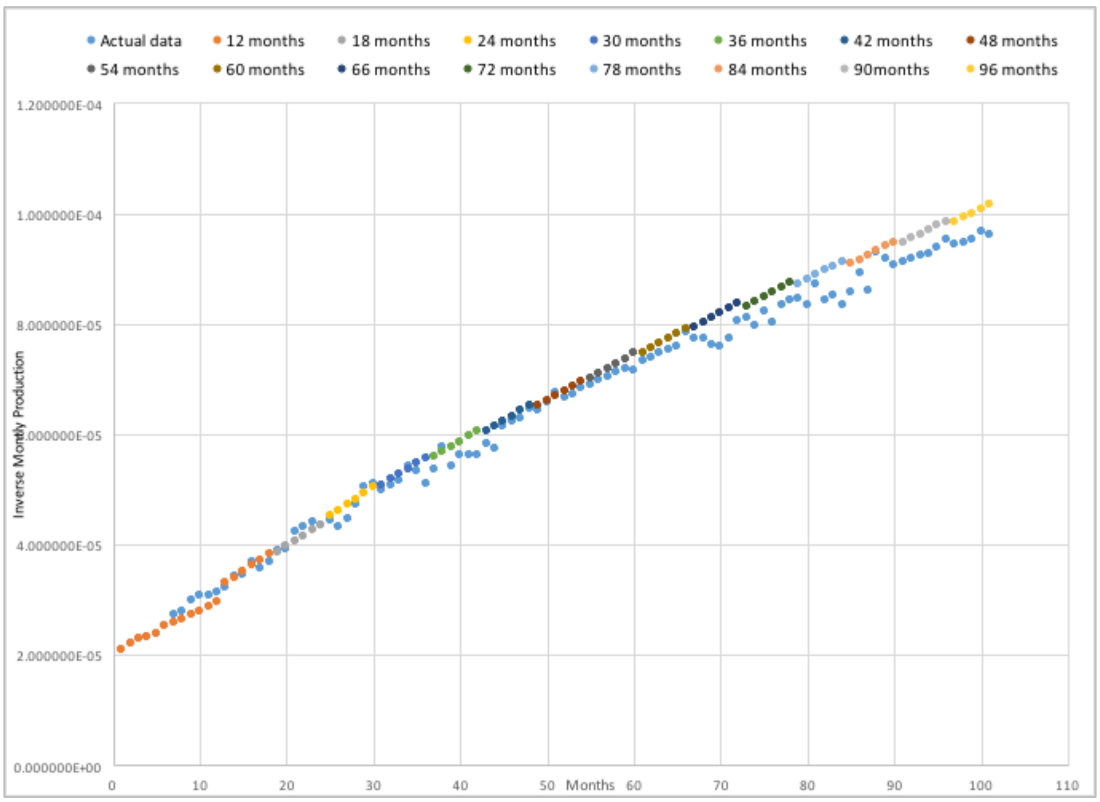

FIGURE 19. WELL-1 COMPARISON OF THE CONTINOUS PREDICTED AND THE ACTUAL PRODUCTION

D. VERIFICATION

To examine the accuracy of the developed technique, the production data from all other wells in this study were utilized to predict the production rates using the techniques described in the previous section and compare them against actual production rates.

CHAPTER 4. RESULTS AND DISCUSSIONS

The results of the analysis and predictions for each well is described in the following sections.

4.1 WELL-2

Figure 20 illustrates the application of the Harmonic decline for the entire production data. As it can be observed, the production rates after 35 month show significant variation (noise) and therefore they are not useful for the analysis purposes. Figure 20 clearly indicate that the entire production history follows harmonic decline.

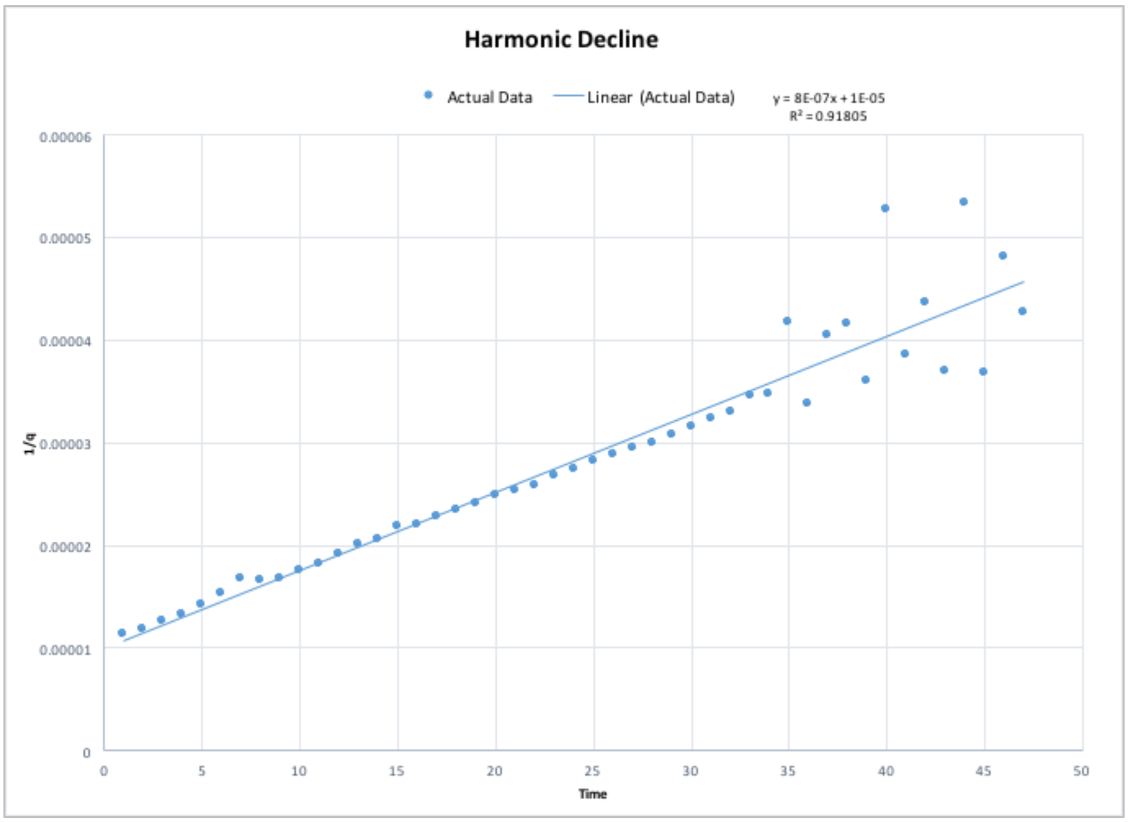

FIGURE 20. HARMONIC DECLINE FOR WELL-2

Figure 21 illustrates the Harmonic Decline for the smoothed data after using polynomial equation to estimate (correct) production rates after 35 months.

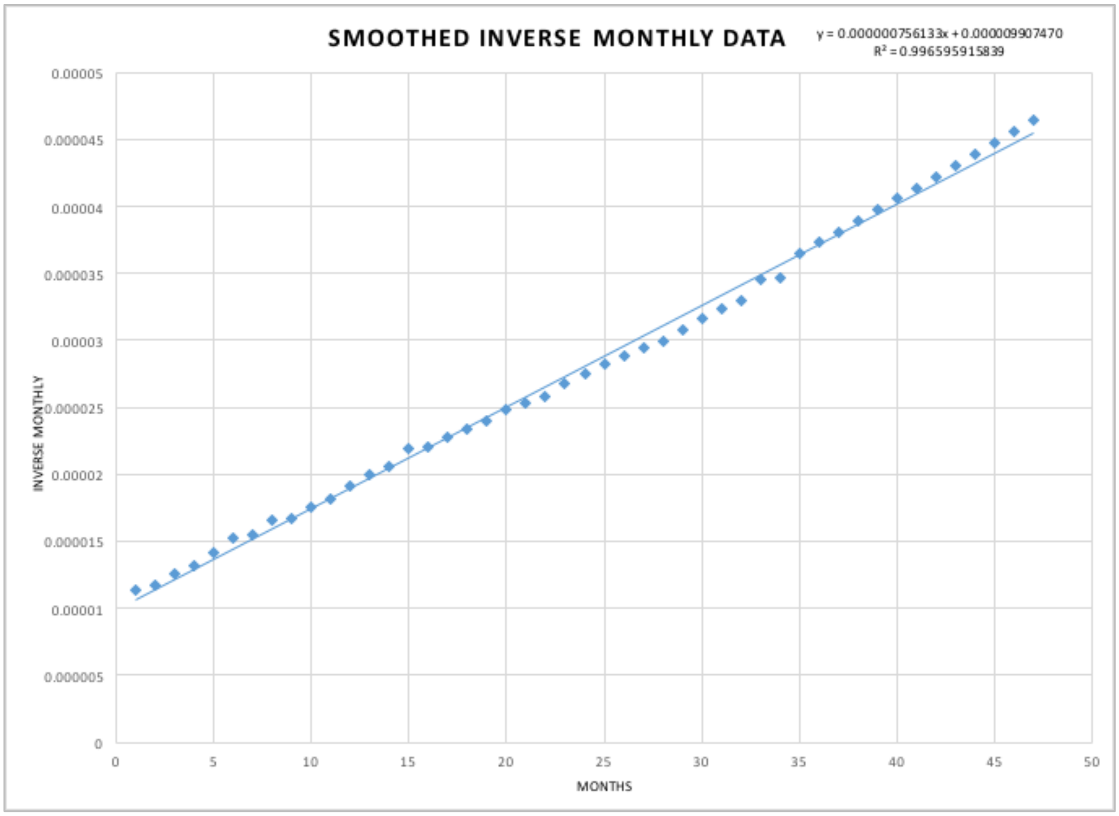

FIGURE 21. HARMONIC DECLINE FOR WELL-2 SMOOTHED DATA

Table 4 summarizes the results of data analysis (the coefficients) as the duration of the periods increased. Figure 22 illustrate how the constants change with increasing the duration of production history. The constants do not exhibit linear trends with time. This is different from what was observed in well No.1 and therefore cannot be used as a consistent method for prediction purposes.

TABLE 4. CONSTANTS BASED ON THE DIFFERENT TIME PERIODS FOR WELL-2

months	*Slope*	*Intercept*	*R^2*
12	7.080E-07	1.054E-05	9.925E-01
18	7.250E-07	1.047E-05	9.964E-01
24	7.080E-07	1.060E-05	9.978E-01
30	6.990E-07	1.068E-05	9.987E-01
36	7.150E-07	1.049E-05	9.977E-01
42	7.400E-07	1.015E-05	9.966E-01
47	7.561E-07	9.907E-06	9.966E-01

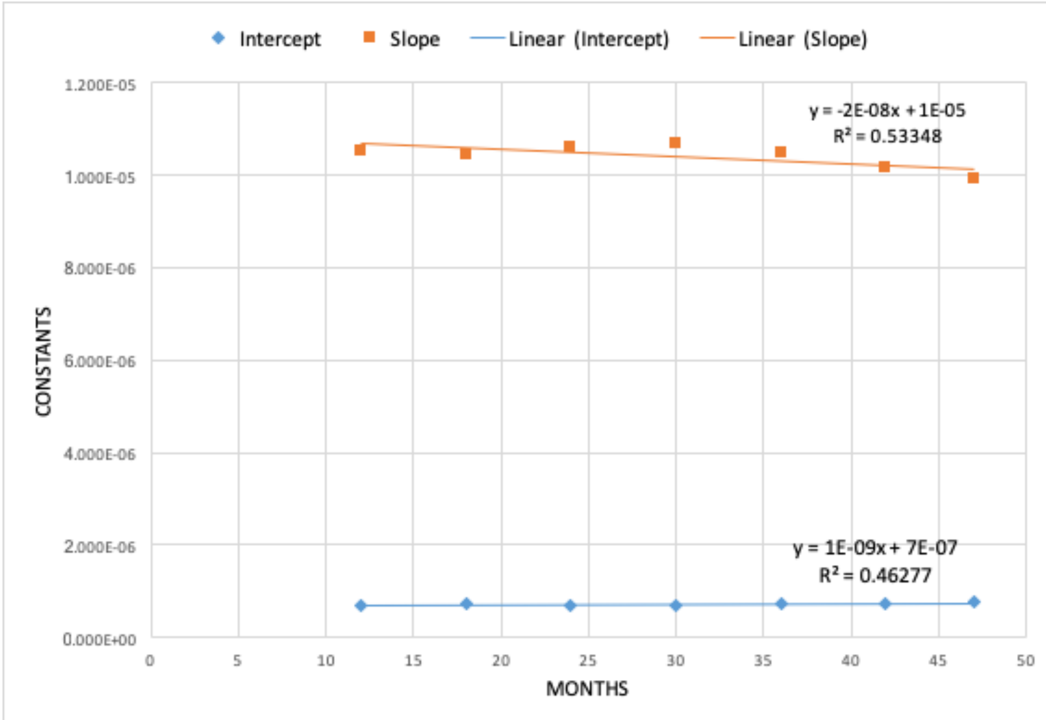

FIGURE 22. THE SLOPE AND THE INTERCEPT VS TIME

Figure 23 illustrate the continuous prediction results for well-2 and compares it against the actual production history. As can be observed, the predicted production rates are very close to the actual rates.

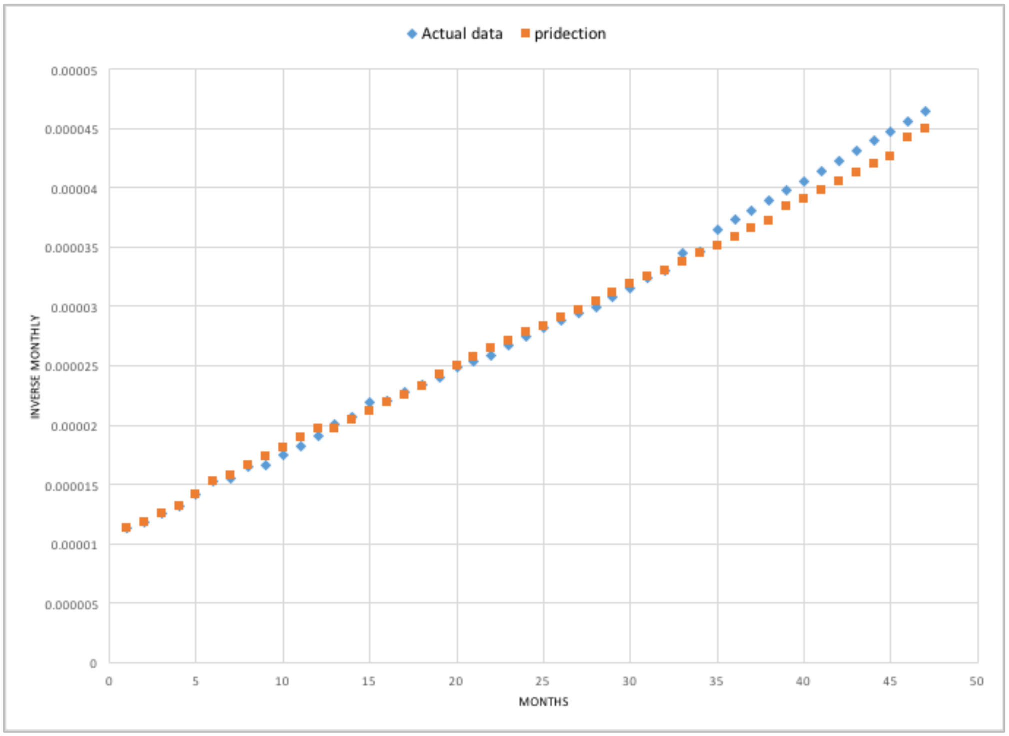

FIGURE 23. WELL-2 COMPARISON OF THE CONTINOUS PREDICTED AND THE ACTUAL PRODUCTION

4.2 WELL-3

Figure 24 illustrates the application of the Harmonic decline for the entire production data which again confirms that the entire production history follows harmonic decline.

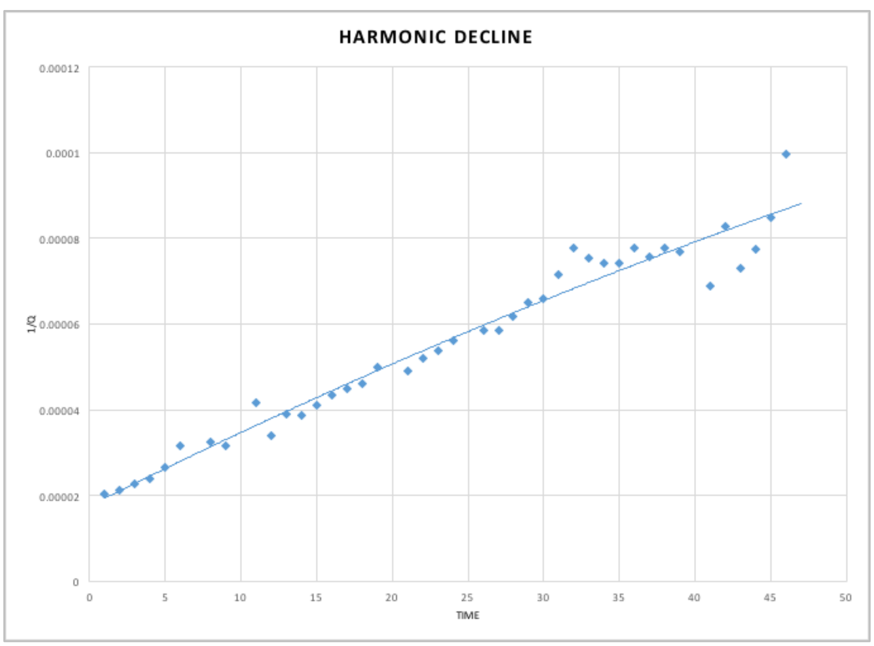

FIGURE 24. HARMONIC DECLINE FOR WELL-3

Figure 25 illustrates the Harmonic Decline for the smoothed data after using polynomial equation to estimate (correct) production rates.

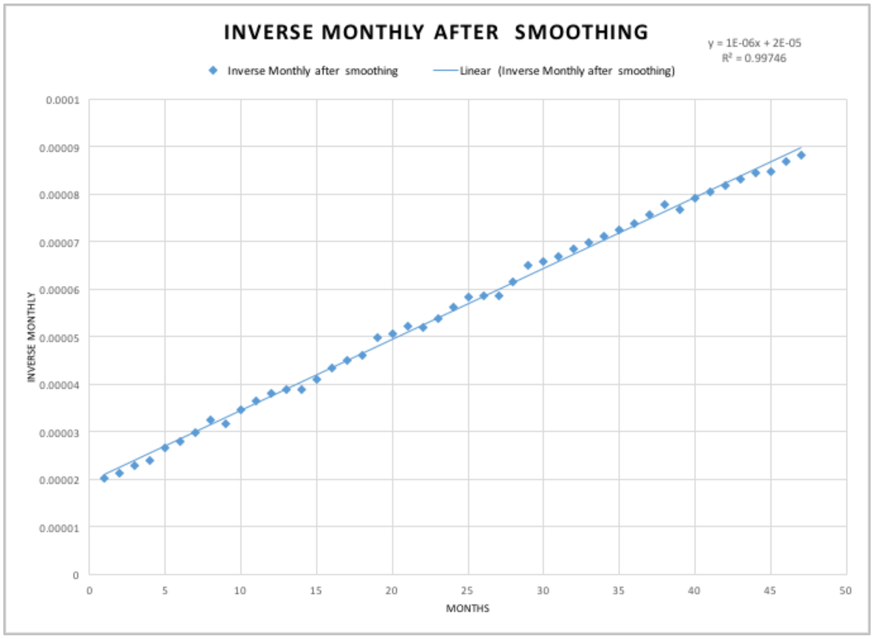

FIGURE 25. HARMONIC DECLINE FOR WELL-3 SMOOTHED DATA

Table 5 summarizes the results of data analysis (the coefficients) as the duration of the periods increased. Figure 26 also shows the inconsistency of trends with time for the constants.

TABLE 5. CONSTANTS BASED ON THE DIFFERENT TIME PERIODS FOR WELL-3

Months	*Slope*	*Intercept*	*R^2*
12	1.646E-06	1.814E-05	9.900E-01
18	1.540E-06	1.868E-05	9.927E-01
24	1.566E-06	1.852E-05	9.949E-01
30	1.557E-06	1.859E-05	9.960E-01
36	1.548E-06	1.870E-05	9.976E-01
42	1.526E-06	1.901E-05	9.978E-01
47	1.498E-06	1.943E-05	9.975E-01

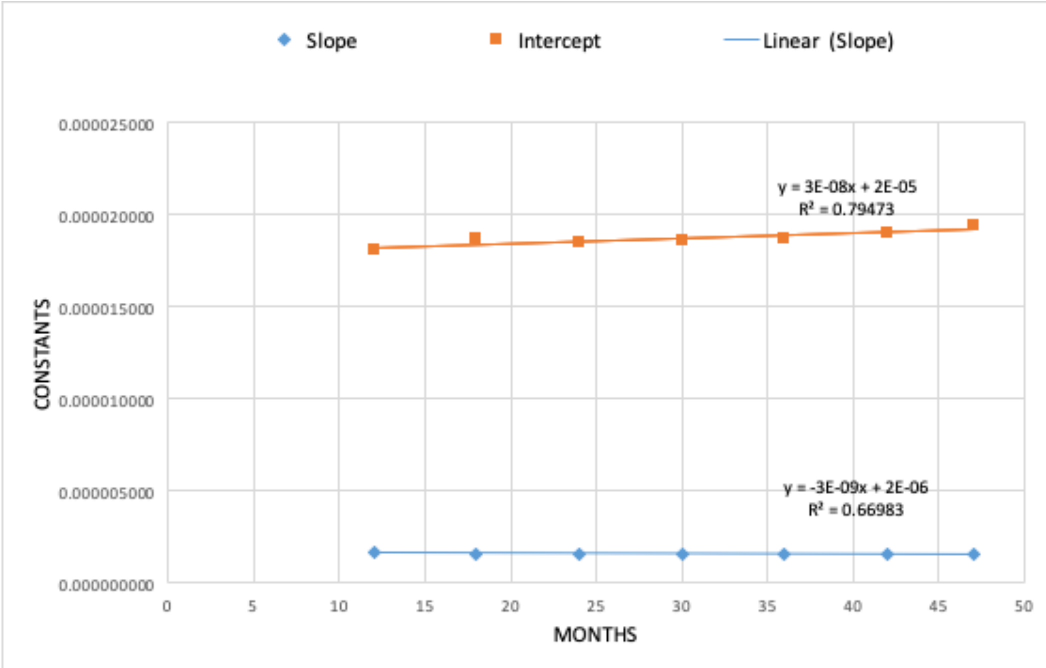

FIGURE 26. THE SLOPE AND THE INTERCEPT VS TIME

Figure 27 illustrate the prediction results for well-3. As can be observed, the predicted production rates are very close to the actual rates.

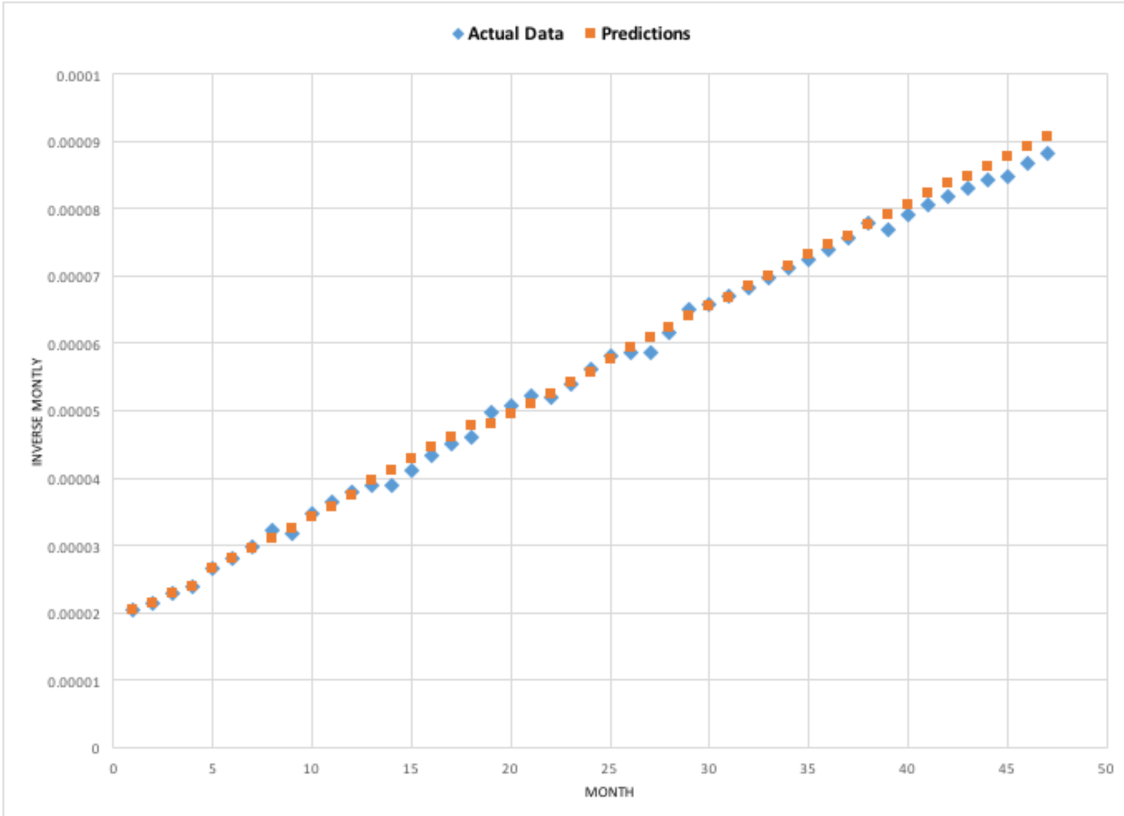

FIGURE 27. WELL-3 COMPARISON OF THE CONTINOUS PREDICTED AND THE ACTUAL PRODUCTION

4.3 WELL-4

Figure 28 illustrates the application of the Harmonic Decline for the entire production data for Well-4. As can be observed from Figure 28, two separate decline trends (lines) appear to be present. This is most likely the result of the well workover or back-pressure change after 50 months causing a change in the slope of the line. Therefore, the production history was separated into 2 parts (4A and 4B) and each part was analyzed separately.

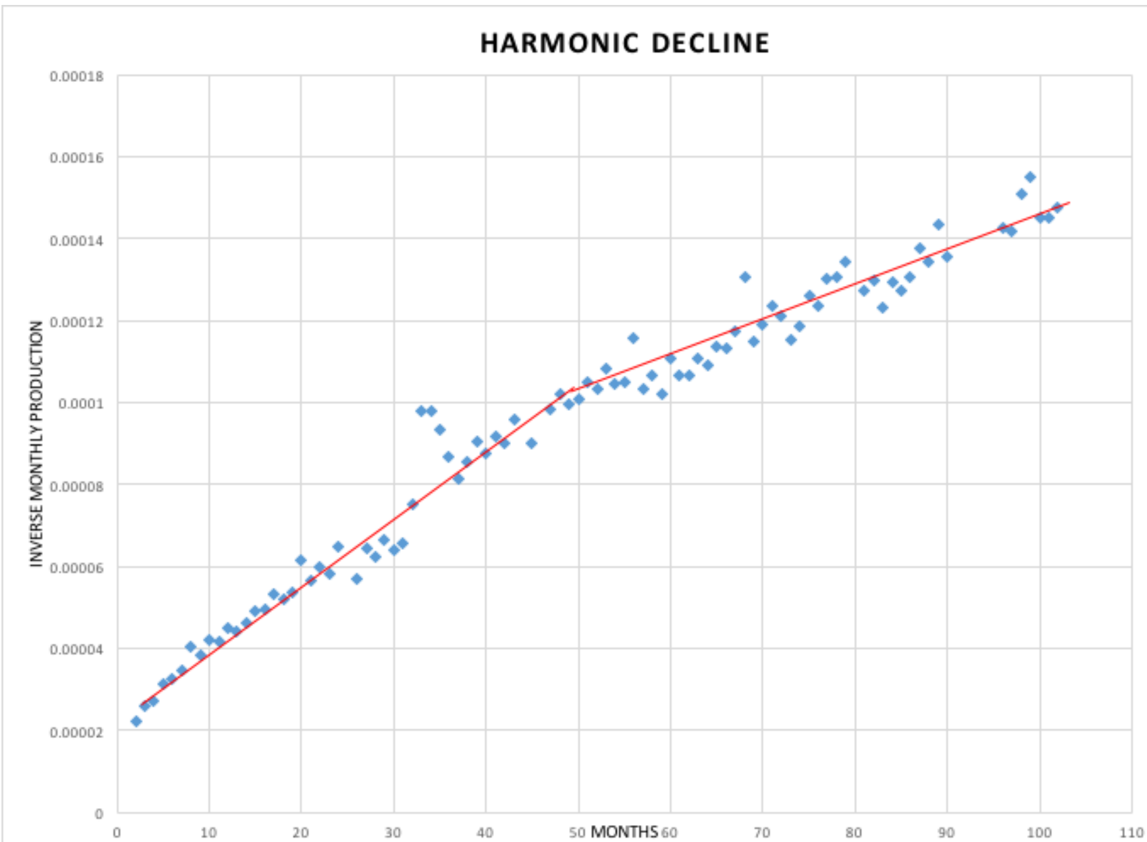

FIGURE 28. HARMONIC DECLINE FOR WELL-4

4.3.1 WELL-4A

Figure 29 illustrates the application of the Harmonic decline to the production history for the first part.

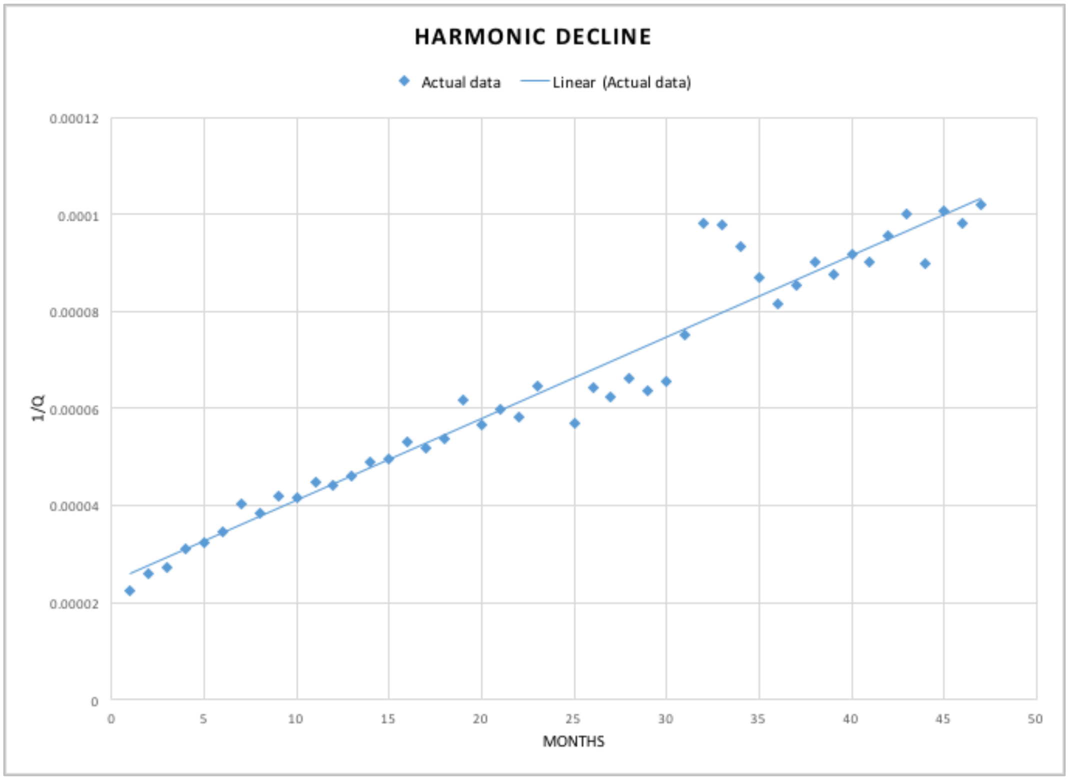

FIGURE 29. HARMONIC DECLINE FOR WELL-4A

Figure 30 illustrates the Harmonic Decline for the smoothed data after using polynomial equation to estimate (correct) production rates.

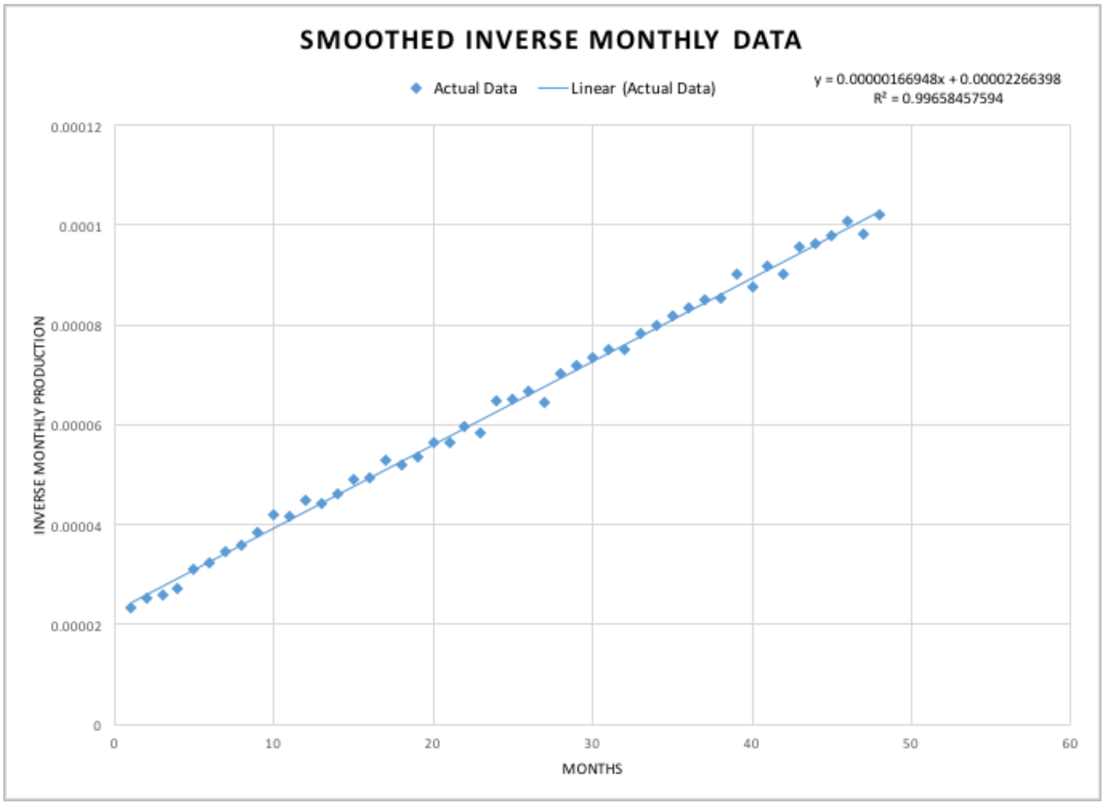

FIGURE 30. HARMONIC DECLINE FOR WELL-4A SMOOTHED DATA

Table 6 summarizes the results of data analysis (the coefficients) as the duration of the periods increased. Figure 31 Also shows the inconsistency in trends similar to the previous wells.

TABLE 6. CONSTANTS BASED ON THE DIFFERENT TIME PERIODS FOR WELL-4A

Months	*Slope*	*Intercept*	*R^2*
12	1.987E-06	2.058E-05	9.883E-01
18	1.797E-06	2.158E-05	9.878E-01
24	1.705E-06	2.224E-05	9.882E-01
30	1.688E-06	2.239E-05	9.916E-01
36	1.688E-06	2.238E-05	9.949E-01
42	1.674E-06	2.258E-05	9.956E-01
48	1.669E-06	2.266E-05	9.966E-01

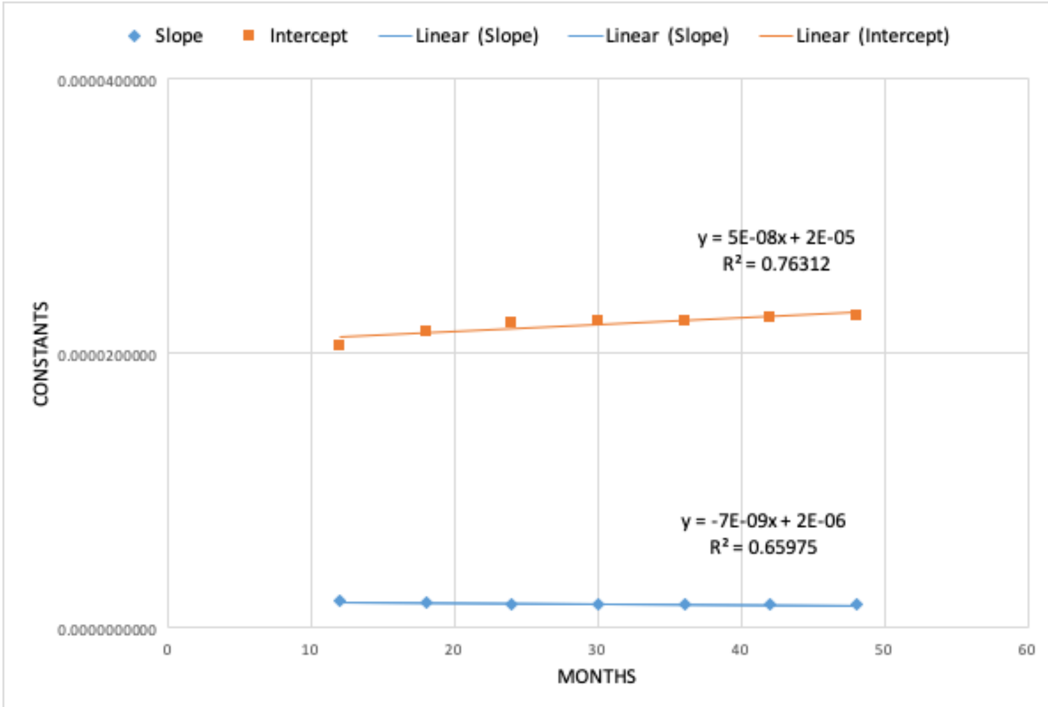

FIGURE 31. THE SLOPE AND THE INTERCEPT VS TIME FOR WELL-4A

Figure 32 illustrate the prediction results for well-4A.

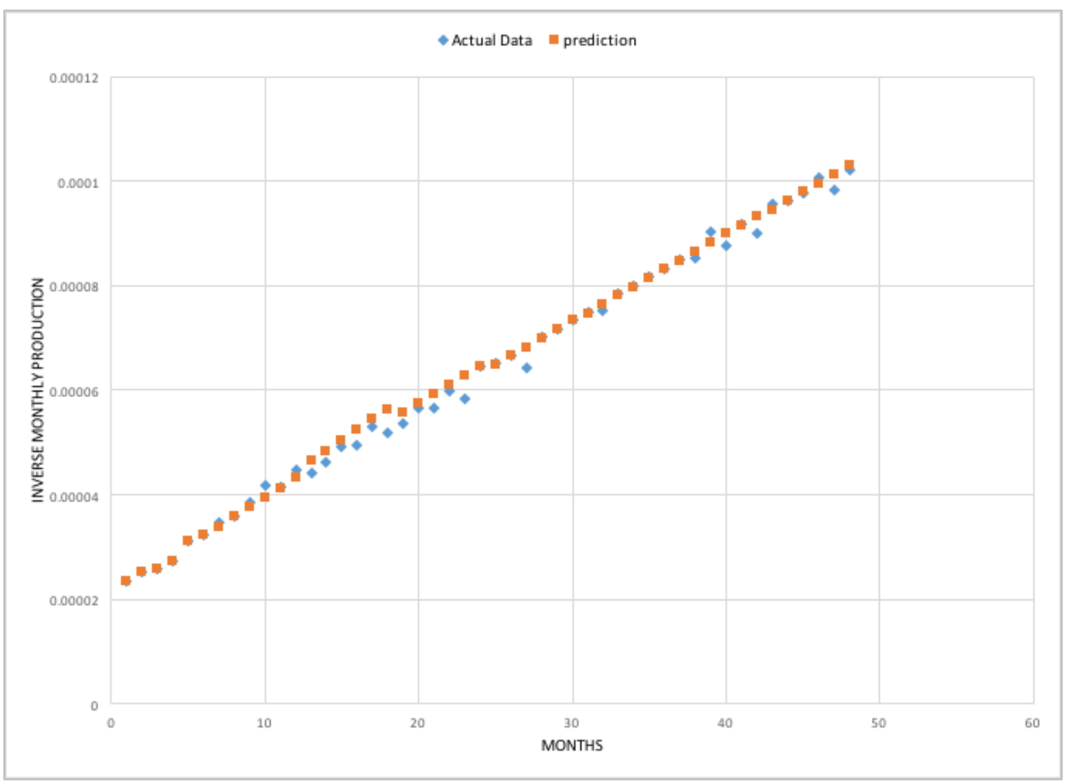

FIGURE 32 WELL-4A COMPARISON OF THE CONTINOUS PREDICTED AND THE ACTUAL PRODUCTION

4.3.2 WELL-4B

Figure 33 illustrates the application of the Harmonic decline to the production history for the second part.

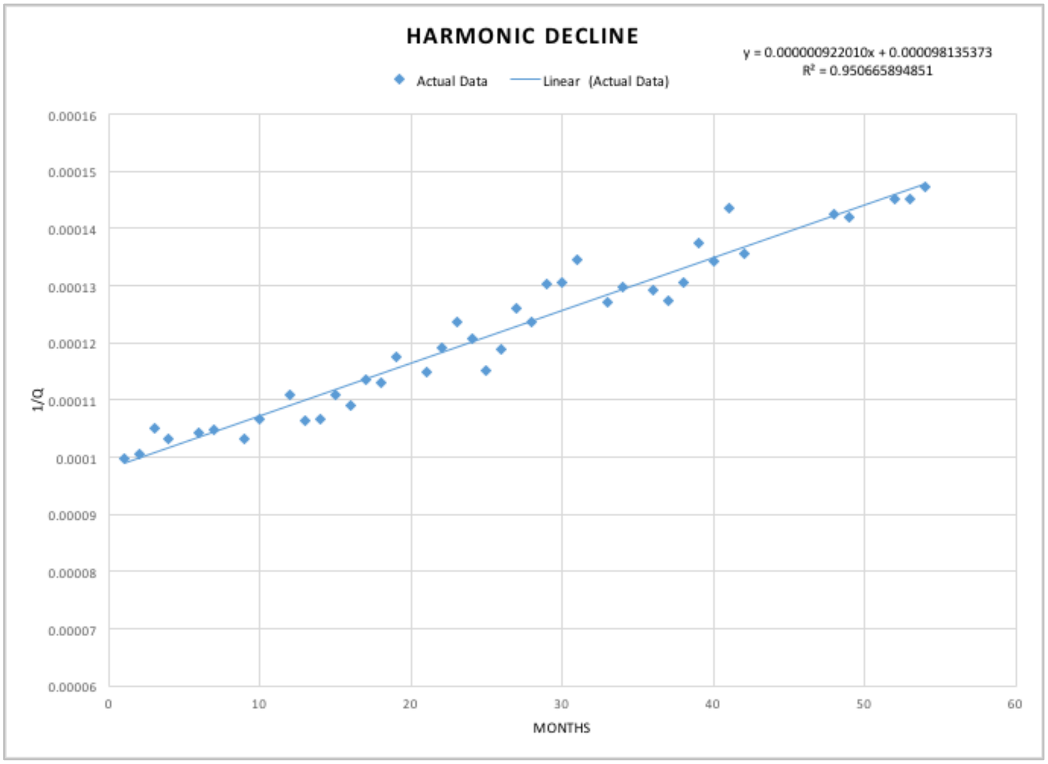

FIGURE 33. HARMONIC DECLINE WELL-4B

Figure 34 illustrates Harmonic Decline for the smoothed data after using polynomial equation to estimate (correct) production rates.

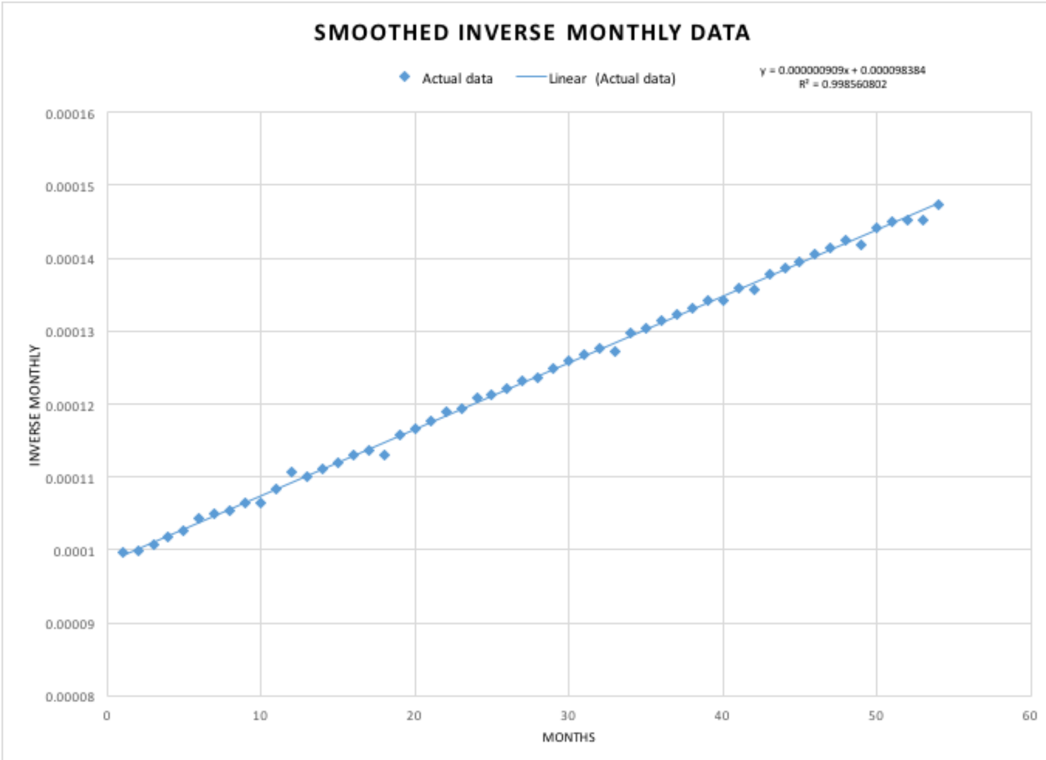

FIGURE 34. WELL-4B SMOOTHED INVERSE MONTHLY DATA

Table 7 summarizes the results of data analysis (the coefficients) as the duration of the periods increased. Figure 35 again shows inconsistency in the trends similar to the previous wells.

TABLE 7. CONSTANTS BASED ON THE DIFFERENT TIME PERIODS FOR WELL-4B

months	*Slope*	*Intercept*	*R^2*
12	9.480E-07	9.811E-05	9.713E-01
18	8.930E-07	9.843E-05	9.855E-01
24	9.200E-07	9.822E-05	9.921E-01
30	9.190E-07	9.823E-05	9.958E-01
36	9.160E-07	9.827E-05	9.969E-01
42	9.120E-07	9.832E-05	9.978E-01
48	9.160E-07	9.827E-05	9.985E-01
54	9.087E-07	9.838E-05	9.986E-01

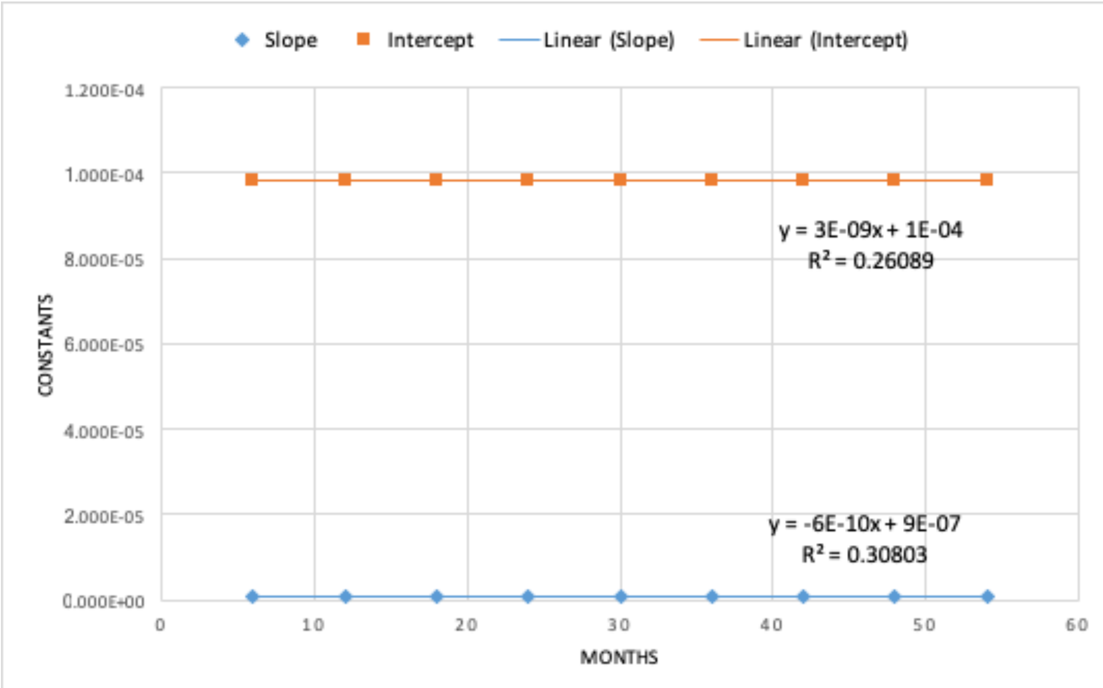

FIGURE 35. THE SLOPE AND THE INTERCEPT VS TIME FOR WELL-4B

Figure 36 illustrate the prediction results for well-4B.

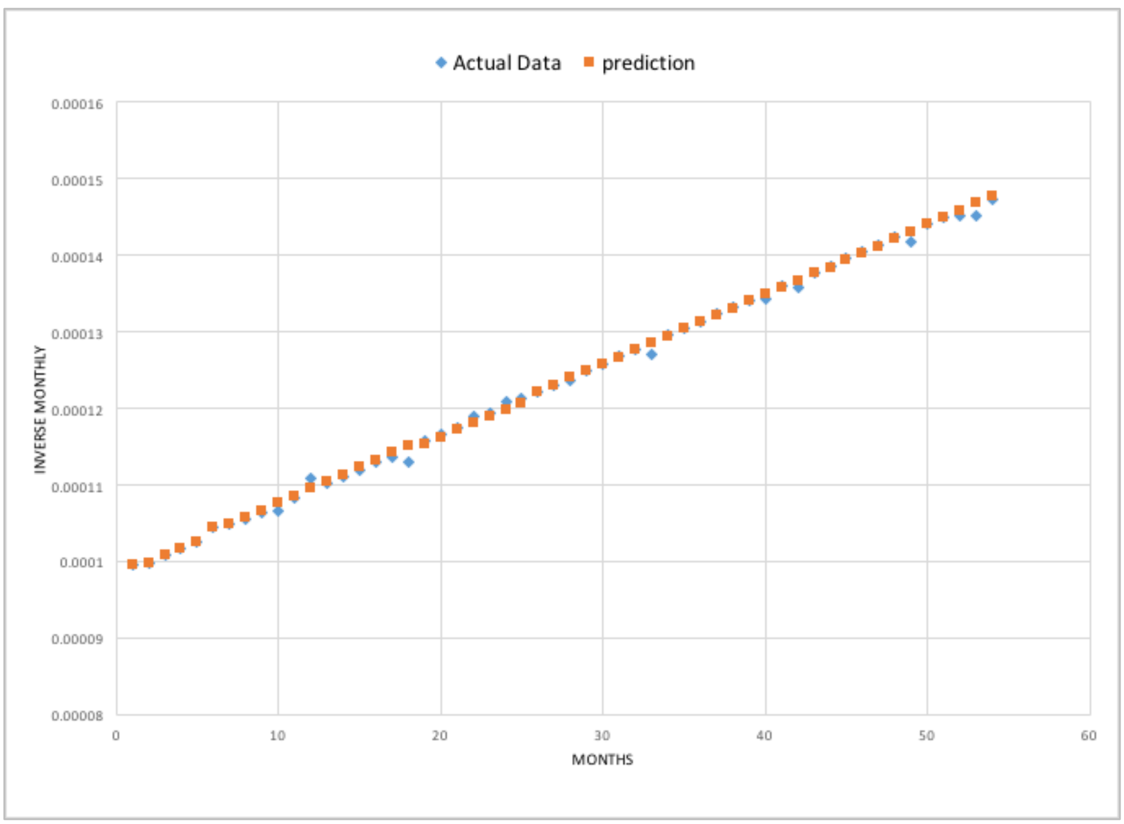

FIGURE 36. WELL-4B CONTINOUS PREDICTED PRODUCTION MATCHED WITH THE ACTUAL PRODUCTION

CHAPTER5. CONCLUSION AND RECOMMENDATIONS

5.1 conclusion

The following conclusions were reached in this study:

1. The long-term production history from several Marcellus Shale horizontal wells in West Virginia clearly indicate that the decline behavior can be closely approximated with Harmonic Decline.
2. The application of the Harmonic Decline to the limited (early) production history cannot provide reliable prediction of the future production rates.
3. The harmonic decline constants change as the duration of the production history increases.
4. A consistent trend for the decline constants cannot be established for all the wells.
5. A prediction technique was developed by continuously adjusting the decline constant as the duration of the production history increases.
6. The prediction technique was found to provide accurate predictions for the wells under study.

5.2 RECOMMENDATIONS

This study utilized production data from 4 horizontal wells in WV. It is recommended to collect and analyze production data from additional Marcellus Shale horizontal wells particularly from other geographical areas (Pennsylvania).

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